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STEM Integration in Biology Learning: A Systematic Literature Review

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Abstract
STEM integration in Biology learning has attracted growing research attention, yet a comprehensive, discipline-specific synthesis of its trends, challenges, and implications has remained unavailable. This study addresses that gap by mapping research trends, identifying implementation challenges, and deriving implications of STEM integration in Biology learning published between 2015 and 2025. A Systematic Literature Review (SLR) was conducted following the PRISMA 2020 framework, encompassing identification, screening, eligibility, and inclusion stages, with searches conducted across Scopus, Web of Science, and Google Scholar. Fifty-five articles meeting the inclusion criteria were analyzed thematically. The results show a significant upward trend in publications, rising from one article in 2019 to seventeen in 2025, with Indonesia as the largest contributor (49.1%), Project-Based Learning as the most widely applied approach (52.7%), and Ecology and Environment as the most frequently studied Biology topic (40.0%). Four major implementation challenges were identified: limited teacher competency in designing interdisciplinary learning, misalignment between curriculum structures and STEM principles, inadequate facilities and resources, and low student motivation and STEM literacy. These findings indicate that advancing STEM-Biology integration requires sustained teacher professional development, broader research coverage across underexplored educational levels and Biology topics, curriculum reform, and more equitable implementation across Indonesia's regions.

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1. INTRODUCTION

21st-century education requires individuals to develop critical thinking skills, problem-solving abilities, and adaptability to rapidly evolving technological advancements (Le et al., 2023). In this context, STEM education, which integrates science, technology, engineering, and mathematics, is widely regarded by many countries worldwide as an essential approach for preparing younger generations to face global challenges (Leavy et al., 2023). Many countries have established STEM as a national education policy priority due to its strong association with economic growth, innovation, and national competitiveness in the international arena (Abdi et al., 2024). In fact, nine out of ten occupations projected to grow by 2025 are in STEM-related fields, making workforce readiness in this area an essential and unavoidable necessity (Jamaluddin et al., 2025). The growing attention to STEM is also reflected in the surge of scientific publications in this field, with more than 71.59% of total STEM publications over the past decade published between 2019 and 2023, indicating increasing global recognition of the role of STEM in preparing learners for a technology-driven economy (Abdi et al., 2024).

The integrated STEM approach is considered effective when linked to real-life problems, such as environmental, health, and biodiversity issues, thus providing a meaningful learning context for K-12 students (Le et al., 2023). The integration of STEM in science learning not only aims to strengthen content mastery, but also encourages the development of higher-order thinking skills, scientific literacy, and awareness of global sustainability issues that are in line with the Sustainable Development Goals (Sihombing et al., 2025). The integrated STEM approach in Biology learning allows for the creation of contextual learning experiences where students are invited to solve problems through the simultaneous integration of science, technology, engineering and mathematics concepts (Yaki, 2022). Thus, STEM-based Biology learning is believed to be able to create a more meaningful learning experience than conventional approaches, because it encourages students to apply cross-disciplinary knowledge in the context of real challenges, rather than simply memorizing and receiving a one-way transfer of knowledge (Loof et al., 2022).

Researchers around the world have conducted numerous studies on STEM integration in science education, including studies on the effectiveness of STEM on student learning outcomes, motivation, and higher-order thinking skills. However, studies specifically and comprehensively synthesizing the application of STEM in Biology learning remain very limited. Gül et al. (2023) found that most systematic studies on STEM at the K-12 level are still cross-disciplinary in nature, with none specifically synthesizing STEM integration in the context of Biology as a discipline with its own characteristics. This is consistent with broader patterns in the field: existing systematic reviews on STEM education have largely centered on debates about theoretical frameworks and integration principles in general (Portillo-Blanco et al., 2024), rather than examining any single discipline in depth. Where discipline-specific evidence does exist, it tends to be fragmented, capturing isolated aspects such as cognitive or motivational outcomes rather than offering a comprehensive picture of trends, challenges, and implications within a specific field. Jamaluddin et al. (2024) further showed that STEM research in the Asia-Pacific region, including Indonesia, remains dominated by general, cross-disciplinary studies rather than discipline-focused syntheses.

Despite this growing body of research, a clear gap remains. No existing systematic review has specifically and comprehensively synthesized the trends, challenges, and implications of STEM integration within Biology learning as a discipline in its own right. Portillo-Blanco et al. (2024) addressed STEM broadly across science, technology, engineering, and mathematics without disaggregating findings for Biology specifically. Cao et al. (2025) similarly examined STEM education through a general, cross-disciplinary lens rather than focusing on any single field. This gap is significant because Biology's phenomenological and contextual nature, with its direct ties to real-world issues such as environmental change, health, and biotechnology, gives it distinct pedagogical characteristics that warrant a dedicated, discipline-specific synthesis rather than treatment as one strand within general STEM research.

This study addresses that gap by providing a systematic literature review focused specifically on STEM integration in Biology learning across a ten-year span (2015–2025), synthesizing research trends, implementation challenges, and implications within this discipline. Unlike previous general STEM reviews, this study offers a discipline-specific evidence base that captures patterns unique to Biology education, such as the prominence of ecology- and environment-related topics and the comparatively limited attention given to areas like cell biology and zoology.

To address the identified research gaps, the Systematic Literature Review (SLR) approach was chosen as the research method. SLR is a systematic, explicit, comprehensive, and reproducible research approach that identifies, evaluates, and synthesizes various studies conducted by previous researchers (Castillo-Martínez et al., 2024). In contrast to conventional literature reviews, which tend to be unstructured, SLRs use strict search protocols and clear inclusion and exclusion criteria, resulting in a more objective, valid, and less biased synthesis (Page et al., 2021). This advantage makes SLR very suitable for mapping trends, identifying challenges, and formulating the implications of STEM integration in Biology learning in a comprehensive and scientifically accountable manner.

Based on this gap, this study aims to map research trends, identify implementation challenges, and formulate the implications of STEM integration in Biology learning between 2015 and 2025, using a Systematic Literature Review (SLR) guided by the PRISMA 2020 framework.

The significance of this study lies in providing an evidence-based reference that teachers, researchers, and policymakers can draw upon to design more innovative, contextual, and equitable STEM-Biology learning. By consolidating a decade of fragmented findings into a single discipline-focused synthesis, this review is expected to support the advancement of Biology education in Indonesia and contribute to the broader national agenda of strengthening STEM education quality.

Based on the background and research gaps described above, this study addresses the following research questions:

1. What are the research trends in STEM integration in Biology learning from 2015 to 2025?
2. What are the main challenges in implementing STEM integration in Biology learning?
3. What are the implications of STEM integration in Biology learning for teachers, researchers, and policymakers?

As a Systematic Literature Review, this study does not employ formal hypotheses. However, based on the existing literature, the following propositions are put forward:

1. Research on STEM integration in Biology learning has experienced a significant upward trend since 2019, particularly in Indonesia;
2. Implementation challenges are predominantly related to teacher competency, curriculum structure, and resource availability; and
3. Project-Based Learning is the most widely applied approach in STEM-Biology integration across various educational levels.

2. LITERATURE REVIEW

2.1. Concepts, Definitions, and Theoretical Foundations of STEM Education

STEM is an acronym for Science, Technology, Engineering, and Mathematics, referring to an interdisciplinary educational approach that integrates these four fields into a meaningful and contextual learning experience (Nugraha et al., 2024). Rather than positioning the four disciplines side by side, this approach explicitly connects them through real-world problems, enabling students to build a holistic, cross-disciplinary understanding (Portillo-Blanco et al., 2024). This distinction matters because it separates STEM as genuine integration from STEM as mere juxtaposition of separate subjects, a distinction that becomes especially relevant when evaluating how deeply STEM principles have actually been applied in Biology learning, as discussed later in this review.

Experts distinguish STEM integration into several levels, ranging from multidisciplinary to interdisciplinary and transdisciplinary, in which students apply knowledge from various disciplines to solve real-world problems in an integrated manner (Han et al., 2023). Larkin & Lowrie (2023) describe this as a continuum, from the simplest form of a single discipline to the most complex form of transdisciplinary integration, which requires students to address real-world problems with genuine social dimensions. In practice, the choice of integration level depends heavily on subject context, student characteristics, and teacher readiness to design authentic learning experiences. Within this continuum, Portillo-Blanco et al. (2024) show that the approach most widely applied in science learning sits closer to the interdisciplinary end, explicitly connecting at least two disciplines through structured inquiry and engineering design around real-world problems. This positioning is instructive for Biology learning, since Biology's inherently interdisciplinary subject matter, spanning environmental, health, and biotechnological issues, makes it particularly well suited to this same level of integration rather than superficial multidisciplinary pairing.

Collaborative, problem-based STEM learning finds a strong theoretical foundation in Vygotsky's sociocultural theory. Vygotsky (1978) introduced the Zone of Proximal Development (ZPD) as the distance between the level of development students can achieve independently and the level they can achieve through guidance from adults or collaboration with more competent peers. He further argued that each cognitive function first appears at the interpersonal, social level before being internalized individually, making social interaction a prerequisite for higher-order cognitive development. Rahman (2024) extended this principle to STEM, arguing that complex Biology concepts become more meaningful when constructed through cross-disciplinary collaboration and authentic problem-solving before individual internalization. This theoretical grounding explains why STEM-Biology approaches that emphasize collaboration and scaffolding, such as Project-Based and Inquiry-Based Learning, have consistently been reported as more effective than conventional, individually oriented instruction, a pattern that this review's findings further substantiate.

2.2. Characteristics of Biology Learning Based on STEM

Biology as a scientific discipline possesses characteristics that make it especially well suited to integration with the STEM approach, since its subject matter is inherently tied to real-life problems such as environmental pollution, human health, biotechnology, and biodiversity (Artika et al., 2023). This phenomenological and contextual nature aligns closely with the core principles of STEM, which emphasize authentic problem-solving through cross-disciplinary integration (Reiser et al., 2024). Biology also naturally involves scientific inquiry, data collection and analysis, and evidence-based conclusion drawing, all of which are core practices within an integrated STEM approach (Wan et al., 2023). Taken together, these characteristics suggest that Biology is not merely one of several subjects that can accommodate STEM, but a discipline for which STEM integration is particularly natural and pedagogically justified, a premise that underlies the rationale for this review.

The urgency of STEM integration in Biology learning is growing stronger as 21st-century competencies increasingly require students not only to master content but also to apply cross-disciplinary knowledge in solving complex problems creatively and collaboratively. Empirical evidence supports this urgency. Reiser et al. (2024) found that a cross-domain, design-based STEM approach in Biology learning significantly improved students' conceptual understanding compared to conventional instruction. Wan et al. (2023) showed that effective STEM implementation in science learning fosters higher student engagement while developing higher-order thinking skills. Artika et al. (2023) further demonstrated that an environmental-issue-based STEM approach in Biology measurably improved students' problem-solving abilities. Collectively, these findings indicate that STEM integration in Biology learning is not merely a pedagogical innovation but an urgent educational need, one whose actual trends, challenges, and implications across the field remain insufficiently mapped, motivating the systematic synthesis undertaken in this review.

2.3. Development of STEM Research in Science Learning

Studies on STEM in science education have developed rapidly, especially since 2019, with project-based, problem-based, and inquiry-based learning emerging as the three most dominant approaches studied empirically across various educational levels (Halawa et al., 2024). Cao et al. (2025) conducted a meta-analysis of 66 empirical studies on STEM published between 2000 and 2024 and found that the problem-based approach had the most significant impact on student learning outcomes, with an effect size of 0.54, followed by the project-based approach at 0.45 and the inquiry-based approach at 0.38. Saseendran and Thomas (2025) reported a sharp increase in publications on integrated STEM research in science education after 2018, led by the United States, China, and Australia as the largest contributors, while also identifying teacher readiness, curriculum rigidity, and limited assessment mechanisms as major implementation challenges.

Within this broader STEM research landscape, science, including Biology, occupies a more dominant position than mathematics and technology as a field of study in integrated STEM research (Chiu et al., 2025). However, this dominance in volume does not equate to depth of coverage. Santoso et al. (2025) found that studies on Biology teaching materials in secondary science education still show significant research gaps, particularly regarding comprehensive and systematic STEM integration. Chiu et al. (2025) similarly noted that a synthesis capturing the trends, challenges, and implications of STEM integration specifically within Biology learning remains urgently needed as a guide for future researchers and educators. Taken together, these studies indicate that the prominence of Biology as a research context has not yet translated into a discipline-specific systematic synthesis, reinforcing the rationale for the present review.

3. RESEARCH METHOD

3.1. Research Design

This study employed a Systematic Literature Review (SLR) design guided by the PRISMA 2020 framework as a reporting structure, comprising 27 checklist items to ensure transparency and completeness at every stage of the review, from article identification and selection through to synthesis (Page et al., 2021). An SLR design was selected because it enables a systematic, transparent, and reproducible process for mapping trends, identifying challenges, and formulating implications of STEM integration in Biology learning, in contrast to narrative reviews, which lack standardized search and selection protocols and are therefore more prone to selection bias.

3.2. Population and Sample

The population in this SLR consists of all published articles addressing STEM integration in Biology learning indexed in Scopus, Web of Science, and Google Scholar between 2015 and 2025. The sample comprises 55 articles selected through the PRISMA 2020 selection process described below, based on the following inclusion criteria: (1) published between 2015 and 2025, (2) written in English or Indonesian, (3) addressing STEM integration in Biology or science learning, (4) presented as empirical research or systematic reviews, and (5) available in full text. Articles were excluded if they were conference abstracts without full text, editorials or opinion pieces without empirical or synthesized data, or did not explicitly address STEM integration within a Biology or science education context.

3.3. Data Collection

Article searches were conducted across three major databases: Scopus, Web of Science, and Google Scholar, using the search string ("STEM" OR "STEM Education") AND ("Biology" OR "Biology Learning" OR "Biology Education") AND ("Integration" OR "Integrated"), combined with the Boolean operators AND and OR. The search was restricted to articles published between 2015 and 2025, with the final search conducted prior to manuscript submission.

3.4. Data Analysis

Article selection was conducted through four stages following the PRISMA 2020 process: identification, screening, eligibility, and inclusion. At the identification stage, articles were collected from the three databases and duplicate records were removed. At the screening stage, articles were screened based on titles and abstracts against the inclusion and exclusion criteria described above. At the eligibility stage, articles that passed screening were read in full to confirm their relevance to the research topic. At the inclusion stage, articles meeting all criteria were retained as the final data sources for analysis. This selection process is presented in Figure 1.

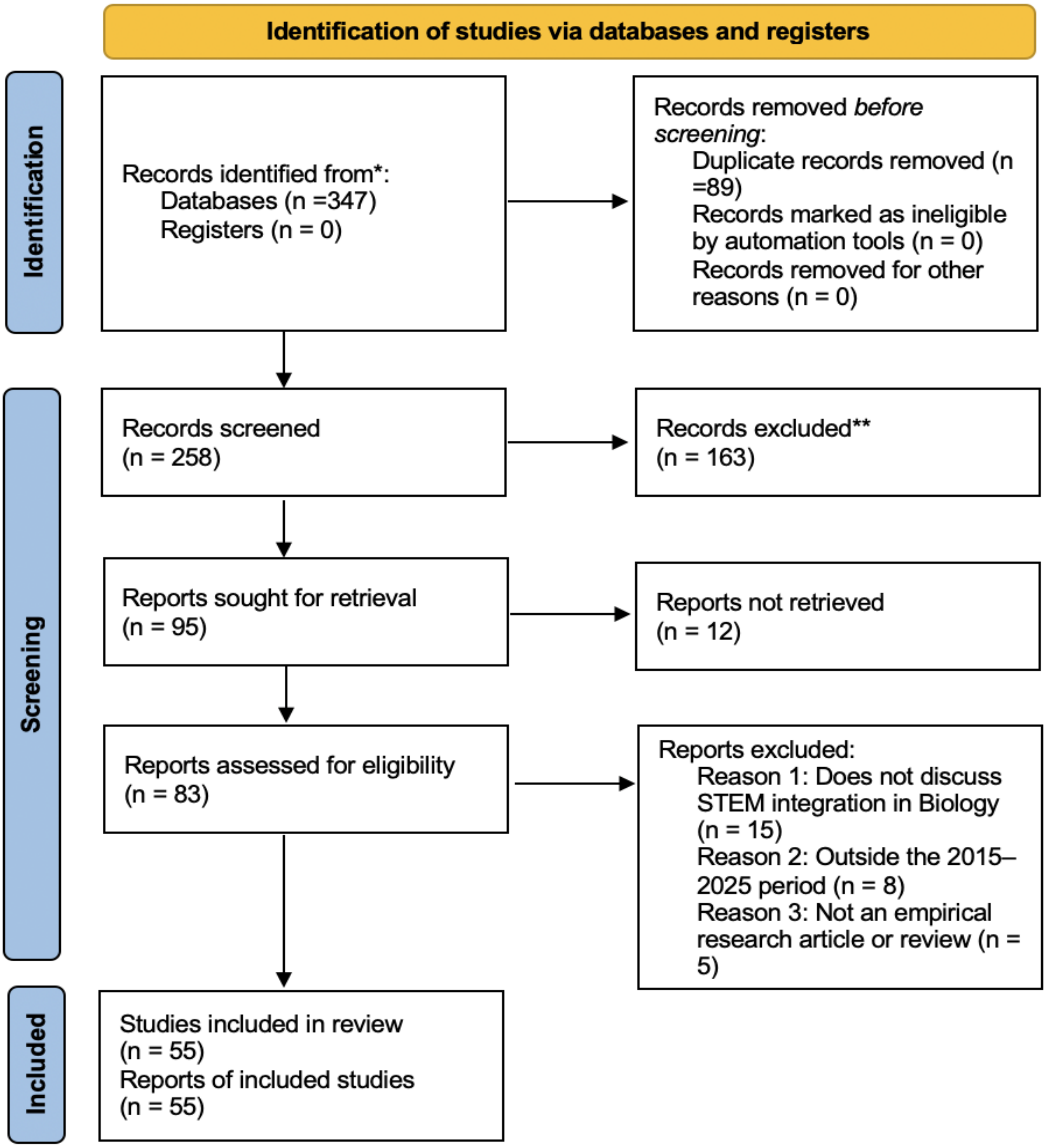

Figure 1. PRISMA 2020 Flowchart of Article Selection Process for Systematic Literature Review on STEM Integration in Biology Learning (2015–2025)

To enhance the rigor of the article selection and data extraction process, the screening and eligibility assessment were reviewed twice at different time points to check for consistency, and any uncertain cases were re-examined against the inclusion and exclusion criteria before a final decision was made. The data extraction sheet was piloted on an initial subset of five articles prior to full implementation to confirm consistency in how key variables, such as STEM approach and educational level, were coded.

Following inclusion, data were extracted using a structured extraction sheet capturing author name, publication year, country of origin, educational level, STEM approach applied, research method, and key findings.

Data analysis was conducted thematically, following Braun and Clarke's (2006) six-phase approach: familiarization with the data, generation of initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the final thematic report. This process enabled the systematic and comprehensive identification of trends, challenges, and implications of STEM integration in Biology learning, corresponding directly to the three research questions guiding this study.

3.5. Research Limitations

This study has several limitations that should be acknowledged. First, the search was limited to three databases (Scopus, Web of Science, and Google Scholar), which may not capture all relevant publications available in other databases or grey literature. Second, only articles written in English or Indonesian were included, which may introduce language bias and exclude relevant studies published in other languages. Third, the scope of this review is limited to the period 2015 to 2025, and findings may not fully reflect developments outside this timeframe. Fourth, the thematic analysis conducted in this study is inherently interpretive and may be subject to researcher bias, despite efforts to maintain consistency and transparency throughout the review process.

4. RESULT AND DISCUSSION

4.1 Research Trends on STEM Integration in Biology Learning

Analysis of the distribution of publication years, presented in Table 1, shows a significant upward trend over the study period, with the number of articles increasing from one in 2019 to seventeen in 2025 and a sharp acceleration beginning in 2022. This pattern is consistent with Saseendran and Thomas's (2025) identification of a broader surge in integrated STEM research publications in science education after 2018, and with Abdi et al.'s (2024) finding that more than 71.59% of STEM publications in the past decade were published between 2019 and 2023.

Table 1. Distribution of Articles by Publication Year

Year	Number of Articles	Percentage
2019	1	1.8
2020	1	1.8
2021	4	7.3
2022	6	10.9
2023	11	20.0
2024	13	23.6
2025	17	30.9
2026*	2	3.6
Total	55	100

**Articles that are already available in early access*

Two developments plausibly explain this acceleration. First, the timing coincides with the global expansion of 21st-century skills agendas in national curricula, which explicitly call for critical thinking, creativity, and problem-solving, precisely the competencies Lafifa et al. (2023) found to be most frequently strengthened through STEM approaches. Second, it aligns with the period following widespread post-pandemic curriculum reforms in several countries, including Indonesia's shift toward the Merdeka Curriculum, which created renewed institutional space for cross-disciplinary, project-based instruction. This is consistent with Wahono et al.'s (2020) finding that STEM produces a moderate effect on student learning outcomes in Asia (ES = 0.69), with its greatest impact on Higher Order Thinking Skills, suggesting that the publication surge reflects not only growing scholarly interest but a genuine, measurable shift in classroom practice rather than a purely bibliometric artifact.

An analysis of the research's country of origin, presented in Table 2, shows that Indonesia is the largest contributor, with 27 articles (49.1%), far surpassing other countries such as Vietnam, the United States, and China/Taiwan, each contributing four articles (7.3%).

Table 2. Distribution of Articles by Country of Origin

Country	Number of Articles	Percentage
Indonesia	27	49.1
Vietnam	4	7.3

Country	Number of Articles	Percentage
United States	4	7.3
China/Taiwan	4	7.3
Australia	2	3.6
Nigeria	2	3.6
Kazakhstan	2	3.6
Turki	2	3.6
Negara lain*	7	12.7
Total	55	100

**Includes Philippines, Austria, India, Germany, Spain, Ecuador, and multi-country studies*

Indonesia's dominance as a research contributor is consistent with Farwati et al.'s (2021) observation that STEM implementation in Indonesia has expanded rapidly since 2014, and with Alberto et al.'s (2024) identification of Indonesia as the largest contributor of science education research over the past five years. This concentration likely reflects growing national policy urgency around STEM education across Southeast Asia more broadly, not only in Indonesia; Nguyen and Le (2024) and Diep et al. (2023) report similar developments in Vietnam, where STEM integration in science learning is increasingly prioritized by educators and policymakers. This suggests that Indonesia's high output may partly reflect a regional trend in STEM policy attention rather than a uniquely Indonesian phenomenon, though it still raises a caution for the generalizability of this review's findings, given that patterns identified here remain disproportionately shaped by the Indonesian and Southeast Asian context rather than representing a globally balanced picture of STEM-Biology integration.

Analysis of educational levels, presented in Table 3, shows that multi-level research is the most common, with 21 articles (38.2%), followed by senior high school (SMA/equivalent) with 20 articles (36.4%).

Table 3. Distribution of Articles by Education Level

Educational level	Number of Articles	Percentage
Multi-Level (Mixed)	21	38.2
High School/Equivalent	20	36.4
Junior High School/Equivalent	8	14.5
University	5	9.1
Elementary School/Equivalent	1	1.8
Total	55	100

The prevalence of senior high school as the second most common educational level is consistent with Farwati et al.'s (2021) finding that senior high school is the most frequently studied level for STEM research in Indonesia, and with Ashari et al. (2021) and Karina et al. (2024), who demonstrated that STEM approaches at this level effectively improve students' higher-order thinking skills (HOTS) and creative thinking. This concentration likely reflects the fact that senior high school Biology curricula, particularly in Indonesia, already contain content most readily suited to STEM integration, such as ecology, genetics, and biotechnology, which offer natural entry points for engineering design and technology-based problem-solving. The prominence of multi-level studies, meanwhile, suggests that researchers increasingly view STEM-Biology integration as a continuum spanning educational levels rather than a level-specific intervention, though this also means the effectiveness of STEM approaches at any single level, such as elementary or tertiary education, remains comparatively underexamined, a gap addressed further in this review's discussion of implications.

At the junior high school level, Benek & Akcay (2022) demonstrated that 24 weeks of socioscientific issue-based STEM activities significantly improved 21st-century skills. Hebebci and Usta (2022) also confirmed that STEM integration at the junior high school level improved students' problem-solving skills and scientific creativity. Meanwhile, at the tertiary level, Abas et al. (2024) and Kasmiruddin et al. (2025) demonstrated that STEM integration significantly improved students' science process skills and critical thinking abilities.

Analysis of STEM approaches, presented in Table 4, shows that Project-Based Learning (PjBL) is the most dominant approach, applied in 29 articles (52.7%), followed by Inquiry-Based Learning in 17 articles (30.9%) and Design-Based/Engineering Design in 15 articles (27.3%).

Table 4. Article Distribution Based on STEM Approach

STEM approach	Number of Articles	Percentage
Project-Based Learning (PjBL)	29	52.7
Inquiry-Based Learning (IBL)	17	30.9

Design-Based/Engineering Design	15	27.3
Problem-Based Learning (PBL)	14	25.5
STEM Terintegrasi Umum	9	16.4
Blended Learning berbasis STEM	4	7.3
STEAM	4	7.3
Contextual Learning	4	7.3
Ethno-STEM	1	1.8

**One article may use more than one approach so that the total percentage exceeds 100%*

PjBL's dominance is consistent with Ningtyas et al.'s (2024) observation that it is the approach most frequently integrated with STEM because it best accommodates authentic, problem-based learning, and with Cao et al.'s (2025) finding that project-based approaches have a significant effect on student learning outcomes. This dominance can also be understood through the sociocultural lens introduced earlier in this review: PjBL inherently requires students to collaborate across roles and expertise to complete a shared product, creating repeated opportunities for the kind of scaffolded, socially mediated learning described in Vygotsky's (1978) Zone of Proximal Development. In this sense, PjBL's prevalence in the reviewed literature may reflect not merely methodological convenience but its structural alignment with a theoretical mechanism already established as effective for complex Biology content, as discussed in the Literature Review.

In the context of PjBL, (Khafah et al., 2023) proved that the PjBL model has a significant effect on students' critical and creative thinking skills on ecosystem concepts. Prajoko et al. (2023) also confirmed that STEM-based PjBL improves students' conceptual understanding of the human locomotor system. For the inquiry approach, Zakiyah et al. (2024) showed that STEM-based Biology learning with the inquiry model has a significant effect on students' creative thinking skills. Xu et al. (2026) added that inquiry-based learning improves students' divergent and convergent thinking with a medium effect size. For the Design-Based approach, Reiser et al. (2024) proved that the design approach produces a more stable long-term increase in biological knowledge than the conventional approach.

In the context of PBL, Simanjuntak and Purwaningsih (2024) confirmed that STEM-integrated PBL improves students' critical thinking skills, scientific literacy, and conceptual understanding. Saragih et al. (2025) similarly showed that STEM integration in PBL and PjBL improves student creativity and learning outcomes across various educational levels in Indonesia. For Ethno-STEM, Sumarni et al. (2022) demonstrated that this approach provides meaningful, contextual learning experiences by connecting local culture with modern science, while Matindike and Ramdhany (2025) confirmed that integrating Indigenous Knowledge into STEM strengthens student engagement and conceptual understanding through contextualized learning. Taken together, the diversity of approaches identified in Table 4, ranging from structured methods like PjBL and IBL to culturally grounded models like Ethno-STEM, suggests that effective STEM-Biology integration is less about adopting a single prescribed method than about selecting an approach that aligns with the specific learning context, available resources, and cultural setting of the classroom.

Analysis of research methods, presented in Table 5, shows a dominance of quantitative methods in 24 articles (43.6%), followed by mixed methods in 19 articles (34.5%) and qualitative methods in 11 articles (20.0%).

Table 5. Distribution of Articles Based on Research Methods

Research Method	Number of Articles	Percentage
Quantitative	24	43.6
Mixed Methods	19	34.5
Qualitative	11	20.0
Others	1	1.8
Total	55	100

The predominance of quantitative methods likely reflects the field's continued emphasis on measuring learning outcomes through effect sizes and standardized instruments, an emphasis illustrated by Zulyusri et al.'s (2023) meta-analysis, which found that Design Thinking-based STEM models improve critical thinking with a large effect size of 0.84. However, this quantitative dominance also has a notable limitation: it privileges measurable outcomes such as test scores and effect sizes while offering limited insight into the classroom processes, teacher decision-making, and implementation barriers that quantitative designs are not built to capture. Rahmawati et al. (2024) addressed this gap by recommending a broader range of methods, including R&D and mixed methods, for future STEM-Biology research, a recommendation this review's findings actively support, given that most of the implementation challenges discussed in the following section were identified through qualitative or mixed-methods studies rather than quantitative ones.

Analysis of the Biology topics studied, presented in Table 6, shows that Ecology and Environment is the most researched topic, appearing in 22 articles (40.0%), followed by General Biology/Science in 16 articles (29.1%) and Genetics and Biotechnology in 12 articles (21.8%).

Table 6. Distribution of Articles by Biology Topic/Material

Biology Topics/Material	Number of Articles	Percentage
Ecology & Environment	22	40.0
General Biology/Science (Cross-Current)	16	29.1
Genetics & Biotechnology	12	21.8
Human Anatomy & Physiology	9	16.4
Physiology & Cell Biology	7	12.7
Botany & Plant Reproduction	7	12.7
Zoology	4	7.3

**One article can cover more than one topic so that the total percentage exceeds 100%*

The prominence of Ecology and Environment is consistent with Le et al.'s (2023) argument that integrated STEM is most effective when linked to real-world problems such as environmental and biodiversity issues, and is further supported by Indrasti and Paidi's (2025) finding that PjBL-STEM applied to environmental change topics produced a high N-Gain of 0.70, alongside Azizah et al.'s (2025) finding that integrated STEM consistently improves critical thinking on ecosystem and pollution topics. This pattern suggests that ecological and environmental content offers the clearest structural fit for STEM's problem-based, engineering-oriented pedagogy, since such topics are inherently tied to tangible, community-relevant problems that lend themselves to design solutions and data-driven inquiry, unlike more abstract or laboratory-confined topics such as cell biology.

In Genetics and Biotechnology, Yaki (2022) demonstrated that an integrated STEM approach to Genetics improved all critical thinking subskills with a large effect size. Wahono et al. (2020) demonstrated that SSI-based STEM integration in Biotechnology significantly impacted students' decisions regarding the issue of organism modification. Temirkhan & Zhumagulova (2025) confirmed that an integrated STEM module in Biotechnology significantly improved students' motivation and academic achievement. In Human Anatomy and Physiology, Chaerunisa et al. (2023) demonstrated that the lab inquiry model and STEM significantly improved students' inquiry skills in the respiratory system. Ding & Zhao (2025) also confirmed that STEM integration in cells and genetics improved students' learning interest, critical thinking, and problem-solving abilities.

In Plant Physiology, Li et al. (2024) demonstrated that 6E-based STEM learning applied to photosynthesis improved students' academic achievement and HOTS, while Usman et al. (2023) showed that STEM-PBL applied to diffusion and osmosis significantly improved learning achievement and information retention. By contrast, Zoology received markedly limited attention, appearing in only four articles (7.3%), pointing to a clear research gap that future studies should address, particularly given that animal behavior, physiology, and conservation offer equally rich opportunities for real-world, design-based STEM problems as ecology does. Donovan and Lamar (2023) similarly emphasized that technology-based infrastructure for Quantitative Biology remains urgently needed to expand the scope of topics addressed through STEM integration. Taken together with Portillo-Blanco et al.'s (2024) identification of real-world problem integration as the core foundation of STEM, with design and inquiry serving as complementary elements depending on topic characteristics, these findings suggest that the uneven distribution of Biology topics in STEM research to date reflects differences in perceived real-world applicability across sub-disciplines rather than differences in their actual pedagogical potential.

4.2 Challenges of Implementing STEM in Biology Learning

Thematic analysis of the key findings across the included articles revealed four recurring categories of challenges in implementing STEM integration in Biology learning, summarized in Table 7, teacher competency, curriculum and assessment, facilities and resources, and student characteristics.

Table 7. Summary of Challenges in Implementing STEM in Biology Learning

Challenge Categories	Indicator	Source
Teacher competency	Limited ability to design interdisciplinary learning, inconsistent implementation in the Classroom	Rahmadayanti et al. (2025); Setiawan et al. (2026); Berry et al. (2025)
Curriculum and assessment	Misalignment of curriculum with STEM principles, rigid assessment system, time constraints	Margot & Kettler (2019); Berry et al. (2025); Tipmontiane & Williams (2022)
Facilities and resources	Lack of laboratory facilities and technology, minimal school support	Rahmadayanti et al. (2025); Megawati (2024); Tipmontiane and Williams (2022)
Charateristics of students	Low STEM motivation and literacy, difficulty in collaboration, suboptimal interdisciplinary understanding	Rahmadayanti et al. (2025); Li et al (2024); Fatimah et al. (2023)

The most dominant challenge concerns teachers' limited competency in designing integrated, cross-disciplinary learning, identified as a major barrier in the Indonesian context by Rahmadayanti et al. (2025). Notably, this competency gap is not always a matter of conceptual understanding: Setiawan et al. (2026) found that although teachers often understand STEM strategies in principle, classroom implementation remains inconsistent due to insufficient training and school support, suggesting the barrier lies more in translating knowledge into sustained practice than in a lack of awareness itself. This is compounded by teachers' tendency to default to their own disciplinary expertise, resulting in suboptimal integration across subjects (Berry & Carpendale, 2025), and is further reflected in Saseendran and Thomas's (2025) identification of teacher preparedness as a persistent barrier to STEM implementation more broadly. Encouragingly, this gap appears addressable: Diep et al. (2023) demonstrated that structured, three-phase training programs measurably improve teachers' competency in designing STEM activities, reinforcing Margot and Kettler's (2019) argument that collaborative support and sustained professional development, rather than one-off training, are essential to closing this gap.

The second challenge concerns curriculum and assessment. Rigid curriculum structures and assessment systems hinder the implementation of integrated STEM (Berry & Carpendale, 2025), while the inherent complexity of Biology content, combined with time constraints, complicates the application of the Engineering Design Process within standard lesson schedules (Tipmontiane & Williams, 2022). This structural rigidity is significant because it points to a mismatch between STEM's inherently open-ended, iterative pedagogy and assessment systems designed around fixed, single-answer outcomes; where more flexible context- and place-based approaches have been adopted, they have simultaneously improved students' cognitive, affective, and skill outcomes (Kopbossyn et al., 2025), suggesting curriculum flexibility itself, not merely teacher effort, is a decisive factor in successful implementation.

The third challenge relates to facilities and resources. Limited laboratory facilities and technology remain significant barriers to implementation (Rahmadayanti et al., 2025), a constraint that persists even at the higher education level, where resource limitations and the need for ongoing professional development continue to pose challenges (Megawati, 2024). Where adequate support facilities are available, such as 3D printing technology, school-based STEM programs have sustained their effectiveness over time (Han et al., 2022), indicating that facility limitations are not a peripheral logistical issue but a direct constraint on whether STEM-Biology programs can be implemented with fidelity at all.

The fourth challenge concerns student characteristics. Low student motivation and STEM literacy hinder implementation (Rahmadayanti et al., 2025), compounded by persistent student difficulties in collaboration and engineering design (Li et al., 2024). These difficulties are likely linked to structural time constraints: the PjBL-STEM model requires a relatively long learning duration (Fatimah et al., 2023), and within limited intervention periods, students' interdisciplinary understanding has not developed optimally (Nagele et al., 2025). Mclure et al. (2022) captured this cumulative effect by identifying a persistent gap between STEM integration as conceptually designed and as actually practiced in classrooms, suggesting that student-level challenges are less a matter of individual student capacity than a downstream consequence of the curricular, resource, and time constraints already discussed above.

4.3 Implications of STEM Integration in Biology Learning

The trends and challenges identified above carry direct implications for teachers and educators, particularly regarding the need to strengthen capacity for integrated learning design. Given its demonstrated significant impact on student learning outcomes (Cao et al., 2025) and its structural alignment with the collaborative, scaffolded learning process discussed earlier in this review, Project-Based Learning represents the most realistic entry point for STEM implementation in Biology classrooms (Ningtyas et al., 2024), rather than more resource-intensive approaches like Design-Based Learning. For contexts where local cultural resources are strong, Ethno-STEM integration offers a contextual alternative that strengthens local wisdom within Biology learning (Sumarni et al., 2021), addressing the student motivation challenges identified above by grounding abstract content in familiar, community-relevant contexts. Teachers are also encouraged to extend STEM integration into Biology topics that remain rarely explored, such as cell biology and zoology (Xu et al., 2026), directly addressing the topic imbalance identified in this review's findings. None of these strategies, however, can succeed if implementation continues to rely on individual teacher initiative; cross-disciplinary collaboration among teachers needs to be systematically facilitated at the institutional level, precisely because the teacher competency challenge identified earlier stems as much from insufficient structural support as from individual capacity (Berry & Carpendale, 2025).

For researchers, this review points to the need for a more comprehensive and sustainable research agenda that directly responds to the gaps identified in its findings. The limited research coverage at the elementary and tertiary levels calls for broadening the research context beyond the secondary-level focus that currently dominates the field, in order to build a more complete picture of STEM-Biology implementation across the educational continuum. Similarly, because the current dominance of quantitative approaches captures learning outcomes but not the classroom processes underlying them, longitudinal and mixed-methods research, including approaches such as R&D (Rahmawati et al., 2024), is needed to examine how implementation unfolds and evolves over time rather than only its endpoint effects. This methodological shift would also allow research to place greater emphasis on the implementation process itself, an emphasis McLure et al. (2022) argue has been neglected in favor of outcome-focused studies. Finally, deepening research into the hierarchy of STEM principles, as proposed by Portillo-Blanco et al. (2025), would provide the conceptual clarity needed to design more systematic and measurable interventions, directly supporting the kind of discipline-specific evidence base this review identifies as still missing.

For policymakers, the implications center on structural support through education system reforms aligned with integrated STEM principles, precisely because the challenges identified in this review, curriculum misalignment, resource limitations, and teacher capacity gaps, are systemic in nature and cannot be resolved through classroom-level pedagogical innovation alone (Rahmadayanti et al., 2025). Addressing curriculum misalignment requires sustainable, needs-based teacher professional development programs to be established as an education policy priority rather than a one-time intervention (Margot & Kettler, 2019). Given that STEM-Biology implementation in this review's findings remains heavily concentrated in specific regions, affirmative action policies are needed to ensure equitable access throughout Indonesia (Farwati et al., 2021), a concern reinforced by the earlier observation that current evidence itself may be geographically skewed. Investment in digital platforms and technology-based learning infrastructure should similarly be prioritized to support STEM-based Biology learning, particularly in under-resourced regions (Donovan & Lamar, 2023). Taken together, these measures point to a common underlying need: providing infrastructure and assessment systems genuinely aligned with STEM principles, rather than STEM being adapted to fit existing, misaligned systems, as a strategic step in national education policy (Saseendran & Thomas, 2025).

5. CONCLUSION

This systematic review of 55 articles published between 2015 and 2025 directly addresses the three research questions guiding this study. First, regarding research trends, STEM integration in Biology learning has shown a significant upward trajectory since 2022, with Indonesia as the largest contributor (49.1%), Project-Based Learning as the most dominant approach (52.7%), and Ecology and Environment as the most frequently studied topic (40.0%). Second, regarding implementation challenges, four major barriers were identified: limited teacher competency in designing interdisciplinary learning, misalignment between curriculum structures and STEM principles, inadequate facilities and resources, and low student motivation and STEM literacy. Third, regarding implications, these findings translate into concrete recommendations for three stakeholder groups. For teachers and educators, strengthening capacity in interdisciplinary learning design through Project-Based Learning offers the most realistic entry point for classroom-level implementation. For researchers, future studies should extend beyond the currently dominant quantitative, cross-sectional designs by employing longitudinal and mixed-methods approaches to capture how STEM-Biology implementation evolves over time, while also addressing the research gap in underexplored topics such as Cell Biology and Zoology and underrepresented educational levels such as elementary and tertiary education. For policymakers, curriculum reform, sustainable and needs-based teacher professional development, and equitable distribution of STEM-Biology implementation across Indonesia's regions should be prioritized. Overall, this review contributes a comprehensive, discipline-specific synthesis that has previously been unavailable in the STEM education literature, offering an evidence-based foundation for advancing STEM-Biology integration both in Indonesia and in comparable educational contexts.

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