RESEARCH ARTICLE

Unveiling the realities of STEM integration in biology: Teachers' perceptions, challenges, and classroom practices in Indonesia

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Abstract

Background: Although STEM plays a critical role in biology education, a persistent disconnect exists between Indonesian teachers' strategic knowledge and their pedagogical practices. **Objectives:** This study examined biology teachers' perceptions of STEM, their knowledge of implementation strategies, and their understanding of implementation challenges. Additionally, it assessed the gap between teachers' strategic knowledge and classroom practices. **Methods:** A mixed-methods design employing a sequential explanatory approach was utilised, consisting of a quantitative survey of 94 high school biology teachers (purposive sampling), followed by semi-structured interviews. The 16-item instrument demonstrated reliability (Cronbach's $\alpha = 0.878$). Quantitative data were analysed descriptively (means and standard deviations), while qualitative data were analysed thematically, utilising triangulation and member checking. **Results:** Teachers exhibited high knowledge of STEM implementation strategies ($M = 4.22 \pm 0.75$), but reported moderate barriers to implementation ($M = 3.62 \pm 0.78$), moderate self-confidence ($\approx M = 3.16$), and moderate to high STEM teaching practices ($M = 3.52 \pm 0.77$). Interviews revealed that STEM was frequently defined as simple technology use; however, components such as engineering design, modelling, meaningful mathematics, and performance assessment were inconsistently applied, largely due to limitations in training, time, facilities, and access to technology. **Conclusion:** Practice-based professional development, a unified STEM framework for biology, and school support–including project time blocks and low-cost tools–are essential for translating knowledge into consistent classroom practice.

Keywords: biology teacher; mixed method; STEM education; teacher perception

Introduction

The current global transformation of biology education emphasises interdisciplinary integration to equip students with increasingly complex future competencies. The shift from content-based instruction to integrated STEM literacy is a crucial element in addressing global challenges in the 21st century (Darmastuti et al., 2025; Kelley & Knowles, 2016). While the integration of STEM is internationally viewed as a catalyst for economic and scientific innovation, in developing nations like Indonesia, this urgency often meets systemic friction (Haeger et al., 2024; Simarro & Couso, 2021). In Indonesia, the urgency of implementing STEM is increasingly evident, as conventional methods are increasingly perceived as less effective at fostering authentic problem-solving skills relevant to industry dynamics (Nurhayati et al., 2020; Shofatun et al., 2024; Suwono et al., 2019). Integrating technology and engineering into the biology curriculum requires a robust pedagogical framework to bridge the gap between theory and practice (Gale et al., 2020; Herlinawati et al., 2024; Roehrig et al., 2021). The success of this innovation depends on the teacher's perception and capacity as the primary decision-maker in classroom learning (Husamah et al., 2025; Phandini et al., 2023).

The STEM approach integrates the disciplines of science, technology, engineering, and mathematics within a coordinated, applicable learning framework (Kelley & Knowles, 2016; Roehrig et al., 2021). This approach emphasises the development of critical thinking skills, problem-solving abilities, and students' creativity in connecting scientific concepts with real-world applications of technology and engineering (Hamdani et al., 2021; Nugraha et al., 2024). Within this context, STEM seeks to equip students with the 21st-century skills, including collaboration, communication, creativity, and problem solving (Stehle & Peters-Burton, 2019). Specifically, the application of STEM in biology education offers opportunities to connect biological concepts with relevant technological and engineering applications, such as experiments involving genetic data analysis using software, the application of biotechnology techniques, or the utilisation of sophisticated tools for observing microorganisms (Alsalamat, 2024; Shofatun et al., 2024). Consequently, biology learning can provide a more immersive experience and prepare students with the practical skills required for professional settings.

Although STEM's potential is promising, its implementation in biology classrooms still faces complex systemic barriers. Numerous studies indicate that while STEM integration has become a focus of educational policy, many teachers lack a comprehensive understanding of STEM concepts and effective strategies for integrating them into their teaching. Research Funke et al. (2025) showed that many teachers have a strong desire to integrate technology into biology instruction. However, Huang et al. (2022) showed that many teachers still lack a deep understanding of STEM concepts and their implementation in teaching practices. Experts argue that teachers' fundamental perceptions of STEM directly mediate the accuracy of its implementation (Margot & Kettler, 2019; Roehrig et al., 2021). Teachers hold positive views of STEM, but a lack of resources impedes its execution (Alsalamat, 2024; Beege et al., 2024; Mafugu et al., 2024). Sellami et al. (2022) also identified key barriers to STEM implementation, including teachers' limited understanding of the STEM curriculum and their limited ability to effectively apply technology in teaching. Collectively, this research suggests that teachers' perceptions of STEM education significantly impact how they design and implement STEM integrated learning experiences in the classroom (Gale et al., 2020; Mafugu et al., 2024). Without a profound understanding of these challenges, STEM integration risks being reduced to mere administrative alterations with little impact on the quality of instructional transformation.

Previous studies have examined variations in perceptions, readiness, and general obstacles faced by science teachers in STEM education (Alsalamat, 2024; Funke et al., 2025; Sellami et al., 2022). However, the literature examining how biology teachers navigate pedagogical and technical obstacles in complex teaching contexts remains limited (Shernoff et al., 2017; Thibaut et al., 2018). Most studies tend to focus on the effectiveness of student learning outcomes or of science disciplines in general, neglecting the dynamics of biology teachers' perceptions as key agents of change in the classroom (Županec et al., 2022). This situation is exacerbated by misrepresentations of STEM stemming from a lack of epistemological understanding of the discipline, which can hinder a deep understanding of STEM's nature (Simarro & Couso, 2021). In addition, rigid institutional influences and variations in mentoring quality in STEM environments reinforce barriers to successful learning transformation (Ashley et al., 2017; Haeger et al., 2024). Therefore, research that explores in depth the relationship between teacher perceptions and systemic barriers, especially by dissecting the implementation gap within Indonesia's education dynamics.

Given the critical integration of biological concepts with technological and engineering elements in contemporary education, exploring teachers' perceptions is a pivotal factor in the success of STEM implementation (Adelana et al., 2024; Županec et al., 2022). This study makes an original contribution by examining the 'implementation gap' between STEM theoretical frameworks and classroom practices in biology education in Indonesia. Unlike previous studies that tend to treat science as a monolith or focus solely on student learning outcomes, this study positions biology teachers as key agents of change.

This study, based on an analysis of 94 validated respondents, uncovers the roots of pedagogical resistance and systemic barriers, serving as an important 'reality check' that bridges global STEM standards with local teaching realities. Specifically, this study aims to (1) analyse biology teachers' perceptions of the essence and urgency of STEM; (2) identify real barriers to cross-disciplinary integration; and (3) evaluate the gap between theoretical understanding and classroom practices. This research can be useful for formulating strategic recommendations to improve national STEM literacy.

Method

Research design

This study employed a mixed-methods, sequential explanatory design, in which quantitative data collection was conducted first through a survey, followed by semi-structured interviews to delve deeper into the survey findings (Alharbi, 2025; Majuddin et al., 2022). A quantitative survey was used to measure biology teachers' perceptions of STEM integration in their learning and their readiness to implement STEM. Qualitative interviews were then used to gain deeper insights into teachers' experiences integrating STEM into biology learning and the challenges they face in the classroom (Setiawan et al., 2025). The subjects of this study were high school biology teachers from various public and private schools in Indonesia. Respondent data are shown in Table 1.

Table 1. Research respondent data

No	Criteria	Grup	Percentage
1	Gender	Male	34
		Female	60
2	Academic Year	< 5	52
		5-10	20
		> 10	22
3	Age	< 30	50
		30-40	34
		> 40	10
	Total		94

Participants

This study involved 94 biology teachers who met strict selection criteria to form a final validated sample. Subjects were selected using purposive sampling, based on the following criteria: (1) Teachers actively teaching biology at the high school or Islamic high school level; (2) Teachers with at least three years of teaching experience; and (3) Teachers who have implemented, or are currently implementing, a STEM approach in biology teaching, either formally through training or informally through classroom initiatives. This research was conducted in schools representing both urban and non-urban contexts to obtain a wider variety of perspectives and experiences.

Data collection techniques

Data collection techniques included a quantitative survey administered via Google Forms and semi-structured interviews. The survey collected quantitative data on teachers’ perceptions of STEM, their readiness levels, and the challenges they encountered during implementation. Teacher perceptions of STEM in learning were assessed using an instrument developed Karpudewan et al. (2022) to evaluate the degree to which teachers understand and support the integration of STEM into biology instruction. The interviews delved deeper into teachers’ experiences and identified practical challenges associated with STEM implementation in the classroom. An interview guide was developed to supplement the quantitative findings and further investigate the application of STEM in biology teaching.

Data analysis

Quantitative and qualitative data were analysed separately but in a complementary manner. A descriptive analysis of the survey characterised biology teachers' perceptions, readiness, and challenges related to STEM implementation and provided an overview of the majority of teachers’ views. This approach is commonly used in STEM education research to broadly understand teachers' perceptions through numerical data before a more in-depth exploration (Margot & Kettler, 2019). Simultaneously, interview data were analysed using thematic analysis to identify key themes from teachers' experiences of integrating STEM into biology teaching. This process involved data collection through semi-structured interviews, data reduction, coding, and (Farhana et al., 2024). interpretation to draw conclusions about teachers' perceptions and challenges in STEM implementation (Creswell & Clark, 2018).

Trustworthiness and ethical considerations

To ensure data validity and trustworthiness, the study employed technical triangulation (comparing survey results, interviews, and document analysis), member checking (verifying findings with respondents), and peer debriefing with experts to maintain objectivity (Birt et al., 2016), and peer debriefing through discussions with experts to maintain objectivity (Ahmed & Brennan, 2021). Although this study did not undergo a formal institutional ethics approval process because it involved a non-invasive survey with minimal risk to adult participants, it still adhered to universal research ethics principles. This includes obtaining informed consent, in which respondents are given a full explanation of the research's purpose and their right to withdraw at any time without consequences. Additionally, Data Confidentiality and anonymity were strictly maintained; all information was used solely for academic purposes and was not shared without permission (British Educational Research Association (BERA), 2018; Swedan et al., 2020). The instrument's reliability is confirmed in Table 2.

Table 2. Instrument reliability (Cronbach's alpha)

Scale	Cronbach's Alpha
Overall 16 Items	0.878
Barriers to STEM Teaching Practices (4 items)	0.708
Knowledge of STEM Implementation Strategies (4 items)	0.912
Teacher Confidence in Teaching STEM (4 items)	0.907
STEM Teaching Practices (4 items)	0.798

Results and Discussion

Participant profile and demographic characteristics

This study involved 94 high school biology teachers from the Jambi and East Java Provinces. The majority of respondents were female (62%), with Bachelor's (S-1) (70%) and Master's (S-2) (24%) educational background. In terms of teaching experience, the sample was dominated by teachers with less than 5 years (60%), followed by those with 5-10 years (13%) and those with more than 10 years (21%). This distribution shows a representative profile ranging from novice to senior levels. Comparative data on indicator scores based on demographic variables are presented in Table 3.

Table 3. Comparison of teacher perception indicator scores on STEM based on demographic variables

Characteristic	Barriers to STEM Teaching Practices		Knowledge of STEM Implementation		Teacher Confidence in Teaching		STEM Teaching Practices	
	M ± SD	t/F	M ± SD	t/F	M ± SD	t/F	M ± SD	t/F
Gender								
Women	3.61±0.79	-0.213	4.21±0.77	-0.282	3.16±0.97	-0.041	3.46±0.82	-1.543
Male	3.65±0.79		4.26±0.69		3.17±0.88		3.70±0.56	
Age								
< 30 Years	3.69±0.71	1.118	4.29±0.65	0.704	3.28±0.86	0.835	3.50±0.71	0.677
30 - 40 Years	3.64±0.83		4.21±0.75		3.01±0.98		3.61±0.78	
> 40 Years	3.31±0.91		4.00±1.07		3.08±1.16		3.31±0.97	
Education								
Bachelor Degree	3.63±0.76	0.192	4.24±0.69	0.303	3.17±0.88	0.183	3.44±0.73	-1.609
Magister Degree	3.59±0.87		4.18±0.92		3.12±1.13		3.75±0.86	
Teaching Experience								
< 5 Years	3.68±0.76	1.340	4.22±0.72	0.501	3.27±0.91	2.659	3.56±0.72	0.340
5 - 10 Years	3.75±0.68		4.38±0.54		3.33±0.98		3.38±0.96	
> 10 Years	3.38±0.89		4.12±0.94		2.75±0.94		3.46±0.83	

Table 3 indicates that no significant differences were observed in the dimensions of barriers, knowledge, and practices across gender, age, or education level ($p > 0.05$). In contrast, a significant difference in self-confidence (teacher confidence) was identified based on teaching experience ($F = 2.659$), with teachers with less than 10 years of experience exhibiting higher self-efficacy than their more experienced colleagues.

Biology teachers' perceptions and strategic knowledge of STEM

The research findings indicate that biology teachers report a high level of knowledge regarding implementation strategies (M = 4.22 ± 0.75), the highest among all measured indicators. At a conceptual level, teachers perceive themselves as understanding the interdisciplinary STEM approach (Nadelson & Seifert, 2017). However, interviews reveal a different picture. Despite strong quantitative scores, the interviews show inconsistency in teachers' understanding. STEM is frequently misinterpreted as simply integrating science and technology, overlooking crucial elements. This was underscored by one participant:

> "For me, STEM is the link between science and technology. However, in biology, I see it more as the application of technology in experiments or observations." (BT1, Male, 30 years old).

Furthermore, interviews with BT2 reveal that teacher knowledge is predominantly declarative. As a result, efforts to integrate other STEM components often appear contrived, as shown in the following excerpt:

> "I know STEM is important for integration, but honestly, I'm still confused about how to incorporate math into biology without making it seem forced in the classroom." (BT2, Female, 40 years old).

Overall, the evidence suggests that teachers' perceptions are narrowly focused on technology as part of experimental design. Therefore, many digital tool-based laboratory activities are described as STEM learning but often lack aspects such as engineering design, substantial mathematical modelling, and authentic interdisciplinary problem-solving (Gale et al., 2020). Compounding this, teachers commonly report insufficient resource support for secondary school STEM implementation, which limits the practical use of strategic knowledge in schools (Le et al., 2021). Research on professional development emphasises that effective STEM implementation relies on systemic supports, including scheduling, access to materials, and collaboration opportunities, not just individual knowledge improvement (Alsalamat, 2024; Nugraha et al., 2024; Shernoff et al., 2017). Without conceptual clarity, teachers' knowledge of implementation strategies is likely to remain superficial and difficult to apply consistently in classrooms (Shambare & Jita, 2024).

STEM implementation challenges

The second objective of the study was to assess teacher barriers and preparedness. The data revealed moderate barriers (M = 3.62 ± 0.78) and moderate self-confidence (M = 3.16 ± 0.9). These findings indicate a paradox. Although teachers possess a high level of strategic knowledge, they do not feel fully "ready" or "confident" to apply it independently in the classroom. The primary barriers identified through interviews were limited formal training and limited school facilities. Perceptions of young teachers (aged <30 years) also demonstrate this. These teachers experienced significant barriers (M = 3.69), showing a high sensitivity to limited school facilities among early to mid-career teachers.

Low self-confidence often stems from a lack of support and limited facilities. Biology Teacher 6 confirmed this in an interview:

> "I feel hesitant to teach STEM comprehensively because of the limited technology and tools available at school." (BT6, Male, 35 years old).

This research found that differing understandings of STEM can lead to inconsistent learning designs. For example, practical activities based solely on digital tools are sometimes categorised as STEM, yet they often lack explicit elements of engineering design, modelling, and authentic cross-disciplinary problem solving. Barriers to STEM implementation among teachers are often related to limited professional development, lack of institutional support, and challenges in operationalising cross-disciplinary integration in the classroom (Cian & Dou, 2024; Tawbush et al., 2020). Theoretically, these barriers arise when the integration of content knowledge, pedagogy, and technology (TPACK) and Pedagogical Content Knowledge (PCK) has not been realised in concrete learning designs (Shambare & Jita, 2024; Silva et al., 2020).

Participant (BT5) further explains institutional barriers and the gap between professional training and school culture:

> "I have attended a training that uses a 'learning by design' approach to make projects integrated. It was very helpful in connecting theory with practice. However, when I returned to

> school, I struggled because there was no follow up. Our school culture still strongly prioritises exam-based outcomes over project-based processes, and there is no consistent system to measure or support our progress after training is over. Without sustained institutional support, it is difficult to sustain these practices." (BT5, Female, 28 years old).

In addition to individual factors, barriers to implementation are influenced by the school's institutional ecology and pedagogical culture (Husamah et al., 2025; Waters, 2022). Therefore, STEM teacher professional development programs typically emphasise a "learning by design/doing" approach to connect theoretical knowledge with real-world practice. However, these programs often struggle with consistent measurement and sustainable implementation support (Huang et al., 2023).
To practically mitigate these barriers, teachers can leverage informal collaboration channels, such as active learning tools or social media groups like WhatsApp. Arikan (2025) showed that the use of active learning tools, such as dichotomous keys within the STEM framework, was able to significantly improve students' self-efficacy, attitudes, and knowledge mastery in biology classes. Apart from that, social media platforms have proven effective in simultaneously supporting interaction, knowledge sharing, and collaborative learning (Ansari & Khan, 2020). Empirical evidence suggests that moderated use of WhatsApp can enhance professional connectivity and teacher self-efficacy, particularly when active discussions about everyday technical solutions are consistently encouraged (Pimmer et al., 2019). Therefore, strengthening interdisciplinary learning design competencies through structured training, providing authentic problem-solving frameworks, and supporting collaborative communities is crucial to ensuring the stable and sustainable implementation of STEM strategies in schools (Phandini et al., 2023; Shernoff et al., 2017).

Actual STEM education practices in the classroom

The third objective was to explore the knowledge-practice gap. The indicator for STEM Learning Practices was moderate to high (M = 3.52 ± 0.77). Respondents have started implementing STEM-integrated teaching, but consistency varies. Master's degree holders (S-2) reported higher practice levels (M = 3.75 ± 0.86) than Bachelor's degree holders (S-1) (M = 3.44 ± 0.73). This suggests academic depth is linked to cross-disciplinary integration. Teachers with fewer than 5 years' experience showed the most active STEM practices (M = 3.56 ± 0.72). STEM practice depends on openness to innovation and a supportive school environment, not just experience (Thibaut et al., 2018).
However, interviews confirmed the important contrast that many activities were labelled 'technology-assisted learning', but few met the recommendations for true 'integrated STEM', which requires the integration of multiple disciplines.

BT4 highlighted this distinction, noting:

> "We use apps for genetic experiments, but our labs aren't equipped to fully support them." (BT4, Male, 32 years old)

Furthermore, respondent BT7 noted that teachers often struggle to use digital apps due to limited physical equipment. This limitation excludes engineering from the process. The following excerpt from the interview illustrates this:

> "So far, my STEM practices have been more digital. For example, I use virtual simulations or mobile apps to help students understand cell division. But when asked to create projects involving engineering design or real-world solutions, we struggle. We know the theory, but our labs don't have the sensors or devices to support such cross-disciplinary integration." (BT7, Female, 38 years old)

Engineering components and cross-disciplinary problem-solving are often neglected. Time constraints and a rigid curriculum contribute to this issue. In Indonesia, STEM implementation depends more on individual pedagogical attitudes than on institutional support (Lupión-Cobos et al., 2022; Sellami et al., 2022). Systemic interventions are needed. Practice-based professional development (PD) and the provision of low-cost STEM tools can help bridge this gap (Huang et al., 2022).

Research implications

This study identifies a clear gap between teachers' cognitive understanding of STEM implementation strategies and their consistent application in classroom practice. While knowledge of implementation strategies is high, actual teaching practices remain only moderate to high, and persistent challenges continue. This shows that understanding alone does not guarantee effective classroom application. Thus, STEM competency should be defined not only as conceptual or procedural knowledge but as the ability to consistently execute integrated, cross-disciplinary learning in practice. Additionally, the study highlights that the effectiveness of STEM implementation depends more on systemic school factors such as support, resources, and collaborative culture than on individual teacher attributes alone (Akiri et al., 2021; Mafugu et al., 2024; Zhou et al., 2023). Qualitative insights further reveal a limited view of STEM as mainly technology use, underscoring the need to reinforce the TPACK–PCK framework. The research ultimately distinguishes between possessing strategy knowledge and demonstrating competency in integrated STEM learning design.

Enhancing the quality of STEM implementation is ineffective if it solely relies on conceptual training. Instead, a comprehensive package of interventions is required, integrating three levels (Figure 1): at the teacher level, professional development should be practice-oriented through the design, enactment, and reflection cycle, microteaching, and lesson study. This enables teachers to design projects, assessment rubrics, and STEM classroom management strategies. At the school level, time management (e.g., project blocks), laboratory and equipment usage policies, and instructional leadership support are necessary. At the ecosystem level (*MGMP biologi*/service/partners), a STEM Biology module bank, a dataset/worksheet repository, and a periodic mentoring scheme are required. This layered approach aligns with evidence indicating that effective professional development requires ongoing support and opportunities for direct classroom application (Huang et al., 2022; Kelley & Knowles, 2016; Margot & Kettler, 2019). Given facility constraints, sustainable policies should promote the concept of "minimum viable STEM" in resource-limited schools. This includes data-driven Biology labs utilising simple tools, local solution design projects emphasising engineering design and evidence-based argumentation, and product/prototype-based performance assessments incorporating data reports and reflections. This fosters an understanding of STEM as adaptive, problem solving and data based argumentation skills, rather than solely dependent on fully equipped laboratories. To address time and formal training limitations, social media-based teacher communities of practice, such as WhatsApp, can be institutionalised as low-cost professional learning communities. These communities facilitate the sharing of teaching tools, discussion of assessments, and problem-solving of implementation challenges. They should be moderated, have defined agendas and output targets (e.g., one module per month), and be connected to coaching (Pimmer et al., 2019). Furthermore, recognising that strategic knowledge is already established, subsequent training should focus on critical components that are frequently absent in the practical phase, such as authentic problem formulation, data modelling and analysis, the engineering design cycle, meaningful integration of mathematics, and process and product assessment. This shift in professional development should ensure that it transitions from merely "knowing STEM concepts" to "producing executable STEM Teacher Level 1. Practice-Oriented Professional Development (Microteaching, Lesson Study), 2. Ability to Design Project 3. STEM Classroom Management Strategies. Ecosystem level (Biology Subject-Specific Teacher Forum (locally known as *MGMP Biologi* or Biology Subject-Specific Teacher Forum) /Service/Partners), 1. STEM biology Module bank, 2. Dataset, 3. Periodic Mentoring Scheme. School Level 1. Time Management 2. Laboratory & Equipment Usage Policies 3. Instructional Leadership Support learning units consistently.

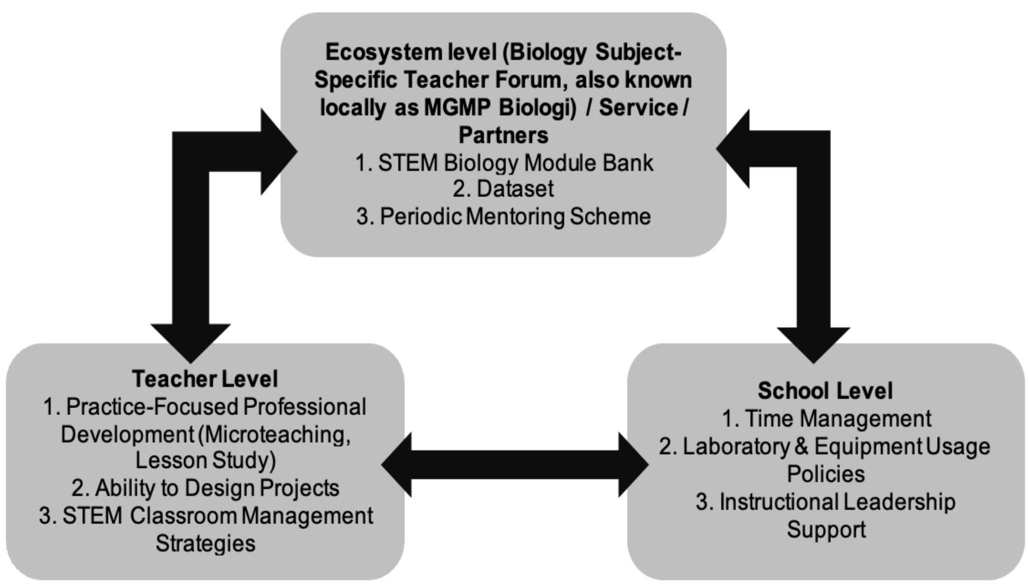

Figure1. Integrated three-level comprehensive intervention for high-quality STEM implementation

In the field of program measurement and quality assurance, these findings suggest that evaluations based solely on self-reports are susceptible to bias. Evidence of implementation would be more robust if supported by classroom observations using STEM integration rubrics (Fan, 2022; Karpudewan et al., 2022; Ong et al., 2024). Additional support could include analysing learning artefacts such as modules, worksheets, and rubrics, as well as documenting student project products. Event based interviews can also be used to capture the pedagogical rationale informing teacher decisions (Fan, 2022). Given the multifaceted nature of constraints, mapping them into more operational sub-dimensions such as time, resources, design competency, and institutional support would enhance the precision of recommendations. This approach helps distinguish between issues that require facility procurement and those that need assessment improvements or collaborative efforts.

A clearer future research agenda should: (1) shift from descriptive studies to causal explanations and intervention testing, by developing structural models to explain the knowledge and practice gap (e.g., mapping pathways from strategic knowledge to self efficacy to practice and examining influences such as school support, facilities, and time) and testing them using methods like structural equation or multilevel modelling; (2) implement longitudinal or quasi experimental studies using an 8–12-week professional development program with coaching, measuring practice changes and sustainability using pretest, posttest, and follow up assesments; (3) use design-based research to produce replicable Biology STEM modules as design principles, module rubric packages, and iterative evidence from multiple cycles; (4) identify the most challenging STEM components (such as engineering design, mathematics integration, or performance assessment) by coding artefacts and observing implementation bottlenecks; (5) conduct contextual research on dominant issues like the digital divide, school policies, instructional leadership, project time allocation, and teacher collaboration culture to generate precise policy recommendations beyond “training needed”; and (6) incorporate student outcomes, including scientific literacy, problem-solving, data based argumentation skills, and project product quality, to show the comprehensive relationship between implementation and learning impact.

Conclusion

This study investigates biology teachers' perceptions of STEM, the obstacles to its implementation, and the disparity between strategic knowledge and classroom practice in Indonesian secondary education. The findings reveal that teachers generally hold positive perceptions of STEM and possess a substantial understanding of implementation strategies. However, despite reported moderate to high levels of STEM teaching practices, their implementation remains inconsistent and predominantly limited to technology-assisted activities rather than comprehensive STEM integration. Key components such as engineering design, modelling, meaningful mathematical integration, and performance-based assessments are not consistently evident in classroom practice. Furthermore, the study identifies structural and contextual barriers as significant contributors to these gaps, including limited formal STEM training, time constraints, inadequate facilities and laboratories, and restricted access to technology. These factors diminish teachers’ confidence in their ability to effectively implement STEM.

Consequently, the most pertinent professional development recommendations are as follows: (1) Clearly align integrated STEM conceptual frameworks within biology by outlining specific minimal components, such as defined goals, targeted learning activities, and focused assessments. (2) Develop and deliver practice-based training that includes opportunities for designing lessons, implementing strategies, engaging in reflection, accessing coaching, and participating in learning studies, with teaching tools provided as practical outputs. (3) Enhance school support through structured project time management and by supplying cost-effective alternative tools, ensuring teachers can consistently implement recommended strategies in the classroom.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

CRediT authorship contribution statement

M. E. Setiawan: Conceptualisation, methodology, formal analysis, supervision, project administration, funding acquisition, writing – original draft, and writing – review & editing. **W. Purnawati**: Investigation, data curation, validation, visualisation, and review & editing. **M. Saefi**: Resources, validation, and review & editing. **B. Putra:** Data curation, investigation, and review & editing. **D. P. Sari**: Resources, investigation, and review & editing. **W. Cahyaadi**: Resources, data curation, and review & editing. **D. D. Putra**: Resources, investigation, and data curation. **F. Z. A. Sapawer**: Resources, investigation, and data curation. **N. Kusmahardhika**: Resources, investigation, and data curation.

Declaration of the use of AI

During the preparation of this work, the authors utilised Gemini-Pro for language alignment and to reduce typographical errors in the manuscript. Following this process, the authors reviewed and edited the content as necessary and accept full responsibility for its publication.

References

Adelana, O. P., Ayanwale, M. A., & Sanusi, I. T. (2024). Exploring pre-service biology teachers' intention to teach genetics using an AI intelligent tutoring—Based system. *Cogent Education*, *11*(1), 2310976. https://doi.org/10.1080/2331186X.2024.2310976

Ahmed, F. U., & Brennan, L. (2021). A review of methodological diversity within the domain of international entrepreneurship. *Journal of International Entrepreneurship*, *19*(2), 256–299. https://doi.org/10.1007/s10843-021-00291-x

Akiri, E., Tor, H. M., & Dori, Y. J. (2021). Teaching and Assessment Methods: STEM Teachers' Perceptions and Implementation. *Eurasia Journal of Mathematics, Science and Technology Education*, *17*(6), em1969. https://doi.org/10.29333/ejmste/10882

Alharbi, M. S. (2025). Digital transformation and EFL anxiety: A mixed-methods study on the impact of online learning on the language acquisition psychology of Saudi Arabian students. *Social Sciences & Humanities Open*, *12*, 101721. https://doi.org/10.1016/j.ssaho.2025.101721

Alsalamat, M. K. M. (2024). Secondary Stage Science Teachers' Perceptions toward STEM Education in Saudi Arabia. *Sustainability*, *16*(9), 3634. https://doi.org/10.3390/su16093634

Ansari, J. A. N., & Khan, N. A. (2020). Exploring the role of social media in collaborative learning the new domain of learning. *Smart Learning Environments*, *7*(1), 9. https://doi.org/10.1186/s40561-020-00118-7

Arikan, K. (2025). The dichotomous key as an active-learning tool in STEM-based biology teaching: Effects on students' self-efficacy, attitudes, and knowledge. *International Journal of Science Education*, 1–21. https://doi.org/10.1080/09500693.2025.2567512

Ashley, M., Cooper, K. M., Cala, J. M., & Brownell, S. E. (2017). Building better bridges into STEM: A synthesis of 25 years of literature on STEM Summer Bridge Programs. *CBE—Life Sciences Education*, *16*(4), es3. https://doi.org/10.1187/cbe.17-05-0085

Beege, M., Hug, C., & Nerb, J. (2024). AI in STEM education: The relationship between teacher perceptions and ChatGPT use. *Computers in Human Behavior Reports*, *16*, 100494. https://doi.org/10.1016/j.chbr.2024.100494

Birt, L., Scott, S., Cavers, D., Campbell, C., & Walter, F. (2016). Member checking: A tool to enhance trustworthiness or merely a nod to validation? *Qualitative Health Research*, *26*(13), 1802–1811. https://doi.org/10.1177/1049732316654870

British Educational Research Association (BERA). (2018). *Ethical Guidelines for Educational Research, fourth edition (2018)*. https://www.bera.ac.uk/publication/ethical-guidelines-for-educational-research-2018-online

Cian, H., & Dou, R. (2024). Masculinized discourses of STEM interest, performance, and competence that shape university STEM students' recognition of a "STEM person". *Journal of Research in Science Teaching*, *61*(5), 1062–1092. https://doi.org/10.1002/tea.21937

Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and conducting mixed methods research* (Third edition, international student edition). Sage.

Darmastuti, S., Isfaeni, H., & Komala, R. (2025). STEM-based flipped classroom: Improve students' critical thinking skills and biological literacy in animalia material. *JPBI (Jurnal Pendidikan*

Biologi Indonesia), *11*(1), 166–178. https://doi.org/10.22219/jpbi.v11i1.39804

Fan, X. (2022). Teachers' perspectives on the evaluation of teacher effectiveness: A focus on student learning objectives. *Teaching and Teacher Education*, *110*, 103604. https://doi.org/10.1016/j.tate.2021.103604

Farhana, Z., Khan, A. S., & Chowdhury, S. A. (2024). ICT in biology education: Teachers' readiness and implementation challenges in the context of Bangladesh. *Discover Education*, *3*(1), 175. https://doi.org/10.1007/s44217-024-00273-w

Funke, M., Bergmann-Gering, A., Müller, K., & Zabel, J. (2025). Pre-service teachers' beliefs on the subject-specific use of digital media in biology classrooms. *Technology, Knowledge and Learning*, *30*(2), 789–807. https://doi.org/10.1007/s10758-024-09800-y

Gale, J., Alemdar, M., Lingle, J., & Newton, S. (2020). Exploring critical components of an integrated STEM curriculum: An application of the innovation implementation framework. *International Journal of STEM Education*, *7*(1), 5. https://doi.org/10.1186/s40594-020-0204-1

Haeger, H., Bueno, E. H., & Sedlacek, Q. (2024). Participation in undergraduate research reduces equity gaps in STEM graduation rates. *CBE—Life Sciences Education*, *23*(1), ar11. https://doi.org/10.1187/cbe.22-03-0061

Hamdani, A., Abdulkarim, A., P, D. C., & Nugraha, E. (2021). Vocational Education in the Industrial 4.0 Era: Challenges and Opportunities. *Proceedings of the 6th UPI International Conference on TVET 2020 (TVET 2020)*. 6th UPI International Conference on TVET 2020 (TVET 2020). https://doi.org/10.2991/assehr.k.210203.081

Herlinawati, H., Marwa, M., Ismail, N., Junaidi, Liza, L. O., & Situmorang, D. D. B. (2024). The integration of 21st century skills in the curriculum of education. *Heliyon*, *10*(15), e35148. https://doi.org/10.1016/j.heliyon.2024.e35148

Huang, B., Siu-Yung Jong, M., Tu, Y.-F., Hwang, G.-J., Chai, C. S., & Yi-Chao Jiang, M. (2022). Trends and exemplary practices of STEM teacher professional development programs in K-12 contexts: A systematic review of empirical studies. *Computers & Education*, *189*, 104577. https://doi.org/10.1016/j.compedu.2022.104577

Huang, Y., Cox, A. M., & Cox, J. (2023). Artificial Intelligence in academic library strategy in the United Kingdom and the Mainland of China. *The Journal of Academic Librarianship*, *49*(6), 102772. https://doi.org/10.1016/j.acalib.2023.102772

Husamah, H., Azizah, J., Permana, T. I., Setyaningrum, Y., & Hindun, I. (2025). Mitigating teacher professionalism problem in Indonesia: What Scopus AI tell us? *Jurnal Pendidikan Profesi Guru*, *6*(2), 40–50. https://doi.org/10.22219/jppg.v6i2.37934

Karpudewan, M., Krishnan, P., Ali, M. N., & Yoon Fah, L. (2022). Designing instrument to measure STEM teaching practices of Malaysian teachers. *PLOS ONE*, *17*(5), e0268509. https://doi.org/10.1371/journal.pone.0268509

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education*, *3*(1), 11. https://doi.org/10.1186/s40594-016-0046-z

Le, L. T. B., Tran, T. T., & Tran, N. H. (2021). Challenges to STEM education in Vietnamese high school contexts. *Heliyon*, *7*(12), e08649. https://doi.org/10.1016/j.heliyon.2021.e08649

Lupión-Cobos, T., Girón-Gambero, J., & García-Ruiz, C. (2022). Building STEM inquiry-based teaching proposal through collaborations between schools and research centres: Students' and teachers' perceptions. *European Journal of Educational Research*, *volume–11–2022*(volume–11–issue–2–april–2022), 899–915. https://doi.org/10.12973/eu-jer.11.2.899

Mafugu, T., Nzimande, E., & Makwara, C. (2024). Teachers' perceptions of integrative STEM education in life sciences classrooms. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(11), em2535. https://doi.org/10.29333/ejmste/15624

Majuddin, C., Md. Khambari, M. N., Wong, S. L., Ghazali, N., & Mohd. Norowi, N. (2022). Students' perspectives on the use of differentiated assessment tool: Results from an explanatory sequential mixed-method pilot study. *Contemporary Educational Technology*, *14*(2), ep358. https://doi.org/10.30935/cedtech/11667

Margot, K. C., & Kettler, T. (2019). Teachers' perception of STEM integration and education: A systematic literature review. *International Journal of STEM Education*, *6*(1), 2. https://doi.org/10.1186/s40594-018-0151-2

Nadelson, L. S., & Seifert, A. L. (2017). Integrated STEM defined: Contexts, challenges, and the future. *The Journal of Educational Research*, *110*(3), 221–223. https://doi.org/10.1080/00220671.2017.1289775

Nugraha, M. G., Kidman, G., & Tan, H. (2024). Interdisciplinary STEM education foundational concepts: Implementation for knowledge creation. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(10), em2523. https://doi.org/10.29333/ejmste/15471

Nurhayati, E., RIzaldi, D. R., & Fatimah, Z. (2020). The correlation of digital literation and STEM integration to improve Indonesian students' skills in 21st century. *International Journal of Asian Education*, *1*(2), 73–80. https://doi.org/10.46966/ijae.v1i2.36

Ong, Y. S., Koh, J., Tan, A.-L., & Ng, Y. S. (2024). Developing an integrated STEM classroom observation protocol using the productive disciplinary engagement framework. *Research in Science Education*, *54*(1), 101–118. https://doi.org/10.1007/s11165-023-10110-z

Phandini, I., Miharja, F. J., Husamah, H., Fauzi, A., & Nuryady, M. M. (2023). STEM-PBL integrative electronic module: Is that effective in improving students' critical thinking skills? *Jurnal Inovasi Pendidikan IPA*, *9*(2), 118–126. https://doi.org/10.21831/jipi.v9i2.60871

Pimmer, C., Brühlmann, F., Odetola, T. D., Oluwasola, D. O., Dipeolu, O., & Ajuwon, A. J. (2019). Facilitating professional mobile learning communities with instant messaging. *Computers & Education*, *128*, 102–112. https://doi.org/10.1016/j.compedu.2018.09.005

Roehrig, G., Dare, E., Ring-Whalen, E. A., & Wieselmann, J. (2021). Understanding coherence and integration in integrated STEM curriculum. *International Journal of STEM Education*, *8*, 1–21. https://doi.org/10.1186/s40594-020-00259-8

Roehrig, G. H., Dare, E. A., Ellis, J. A., & Ring-Whalen, E. (2021). Beyond the basics: A detailed conceptual framework of integrated STEM. *Disciplinary and Interdisciplinary Science Education Research*, *3*(1), 11. https://doi.org/10.1186/s43031-021-00041-y

Sellami, A., Ammar, M., & Ahmad, Z. (2022). Exploring teachers' perceptions of the barriers to teaching STEM in high schools in Qatar. *Sustainability*, *14*(22), 15192. https://doi.org/10.3390/su142215192

Setiawan, M. E., Suwono, H., Alias, S. H., Sulisetijono, S., & Nur, H. (2025). Qualitative exploration of factors influencing the development of entrepreneurship courses in select Indonesian universities with fuzzy logic integration. *Qualitative Research Journal*, *25*(2), 203–226. https://doi.org/10.1108/QRJ-03-2024-0051

Shambare, B., & Jita, T. (2024). TPACK: A descriptive study of science teachers' integration of the virtual laboratory in rural school teaching. *Cogent Education*, *11*(1), 2365110. https://doi.org/10.1080/2331186X.2024.2365110

Shernoff, D. J., Sinha, S., Bressler, D. M., & Ginsburg, L. (2017). Assessing teacher education and professional development needs for the implementation of integrated approaches to STEM education. *International Journal of STEM Education*, *4*(1), 13. https://doi.org/10.1186/s40594-017-0068-1

Shofatun, A., Herniani, E., & Mardiani, D. (2024). STEM learning design to train student's system thinking skills on climate change. *JPBI (Jurnal Pendidikan Biologi Indonesia)*, *10*(1), 234–242. https://doi.org/10.22219/jpbi.v10i1.29699

Silva, J. B., Silva, I. N., & Bilessimo, S. (2020). Technological structure for technology integration in the classroom, inspired by the maker culture. *Journal of Information Technology Education: Research*, *19*, 167–204. https://doi.org/10.28945/4532

Simarro, C., & Couso, D. (2021). Engineering practices as a framework for STEM education: A proposal based on epistemic nuances. *International Journal of STEM Education*, *8*(1), 53. https://doi.org/10.1186/s40594-021-00310-2

Stehle, S. M., & Peters-Burton, E. E. (2019). Developing student 21st Century skills in selected exemplary inclusive STEM high schools. *International Journal of STEM Education*, *6*(1), 39. https://doi.org/10.1186/s40594-019-0192-1

Suwono, H., Fachrunnisa, R., Yuenyong, C., & Hapsari, L. (2019). Indonesian students' attitude and interest in STEM: An outlook on the gender stereotypes in the STEM field. *Journal of Physics: Conference Series*, *1340*(1), 012079. https://doi.org/10.1088/1742-6596/1340/1/012079

Swedan, S., Khabour, O. F., Alzoubi, K. H., & Aljabali, A. A. A. (2020). Graduate students reported practices regarding the issue of informed consent and maintaining of data confidentiality in a developing country. *Heliyon*, *6*(9), e04940. https://doi.org/10.1016/j.heliyon.2020.e04940

Tawbush, R. L., Stanley, S. D., Campbell, T. G., & Webb, M. A. (2020). International comparison of K-12 STEM teaching practices. *Journal of Research in Innovative Teaching & Learning*, *13*(1), 115–128. https://doi.org/10.1108/JRIT-01-2020-0004

Thibaut, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., Boeve-de Pauw, J., Dehaene, W., Deprez, J., De Cock, M., Hellinckx, L., Knipprath, H., Langie, G., Struyven, K., Van De Velde, D., Van Petegem, P., & Depaepe, F. (2018). Integrated STEM education: A systematic review of instructional practices in secondary education. *European Journal of STEM Education*, *3*(1) 1-12. https://doi.org/10.20897/ejsteme/85525

Waters, C. (2022). Exploring effective practices of an elementary STEM block program. *Journal of Research in Science, Mathematics and Technology Education*,5(2), 195-225l. https://doi.org/10.31756/jrsmte.532

Zhou, X., Shu, L., Xu, Z., & Padrón, Y. (2023). The effect of professional development on in-service STEM teachers' self-efficacy: A meta-analysis of experimental studies. *International Journal of STEM Education*, *10*(1), 37. https://doi.org/10.1186/s40594-023-00422-x

Županec, V., Radulović, B., & Lazarević, T. (2022). Instructional efficiency of STEM approach in biology teaching in primary school in Serbia. *Sustainability*, *14*(24), 16416. https://doi.org/10.3390/su142416416