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Uncovering the Potential of STEM-Based Biotechnology Materials Biology Learning: A Systematic Literature Review

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abstract

The Science, Technology, Engineering, and Mathematics (STEM) approach has become a key paradigm for improving the quality of 21st-century science education, including biology learning. Biotechnology material, which has broad applications in daily life, can be taught more effectively through STEM integration. This study aims to examine the potential of STEM-based biotechnology learning through a Systematic Literature Review (SLR). The review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure a transparent and systematic process. A total of 50 articles were initially identified from databases such as Google Scholar, Scopus, and Web of Science using the Publish or Perish application. After screening and eligibility assessment, 10 relevant articles were included in the final analysis. The results indicate that STEM-based biotechnology learning enhances students' conceptual understanding, promotes critical thinking, and fosters innovation. However, its implementation still faces challenges, including limited infrastructure, insufficient teacher training, and lack of supporting teaching materials. In conclusion, STEM-based biotechnology learning has strong potential to be integrated into Indonesia's biology curriculum but requires policy support, teacher capacity building, and resource development. This review provides a foundation for developing more effective implementation strategies.

1. Introduction

Education plays a crucial role in preparing human resources capable of addressing increasingly complex global challenges. In this context, science education becomes a key component in fostering critical, creative, and innovative thinking skills required in the 21st century (Hamdiyah et al., 2026; Elladora et al. 2024; Lafifa et al., 2023). Biology, as one of the fundamental disciplines in science education, not only aims to develop students' understanding of living systems but also to connect scientific knowledge with real-world contexts and technological advancements (Saba, 2024; Ilma et al. 2023). Therefore, biology learning is expected to move

beyond theoretical instruction and provide meaningful learning experiences that are relevant to contemporary societal and environmental issues.

One of the essential topics in biology learning is biotechnology, which has wide-ranging applications in various sectors such as health, agriculture, environment, and industry. Biotechnology integrates biological principles with technological innovation to produce useful products and solutions that contribute to human welfare (Rahim, 2023; Monika et al., 2024). Despite its importance, biotechnology learning in schools is often still dominated by teacher-centered and theoretical approaches, limiting students' opportunities to explore its practical applications. As a result, students tend to have a superficial understanding of biotechnology concepts and face difficulties in relating them to real-life problems (Thomas et al., 2026; Pambudi et al. 2024).

In response to these challenges, the Science, Technology, Engineering, and Mathematics (STEM) approach has emerged as a transformative paradigm in science education over the past decade (Wicaksono, 2020; Putri et al., 2024). This approach emphasizes the integration of interdisciplinary knowledge and encourages students to actively engage in learning through inquiry, experimentation, and problem-solving activities. STEM not only strengthens conceptual understanding but also supports the development of essential 21st-century skills such as critical thinking, collaboration, communication, and creativity (Stuppan et al., 2025; Hin et al., 2019)). In biotechnology learning, the STEM approach enables students to connect biological concepts with technological applications and engineering processes, thereby fostering innovation and deeper understanding (Li et al., 2025; Thompson-Lee et al., 2025).

Previous studies have reported that STEM-based learning can improve students' conceptual understanding, increase learning motivation, and enhance higher-order thinking skills (Siswati et al. 2024; Wijayanto et al., 2020). In the context of biotechnology, STEM provides opportunities for students to engage in project-based and problem-based learning activities that integrate theory with real-world issues, such as environmental management, food production, and health technology. However, despite its promising potential, the implementation of STEM-based biotechnology learning still faces several challenges. These include limited infrastructure and laboratory facilities, insufficient teacher competence in integrating STEM components, and the lack of contextual and integrated teaching materials that support effective learning (Lin et al., 2025; Mubarok and Anugrah, 2024).

Several previous studies have explored biotechnology learning and STEM integration separately or within limited contexts. For example, Hin et al. (2019) focused on biotechnology teaching practices at the secondary school level, while Sari et al. (2024) examined digital teaching materials integrating local potential in biotechnology learning. In addition, Hamdiyah et al. (2026) analyzed the effectiveness of ethnoscience-based learning models in improving biotechnology understanding. However, these studies tend to focus on specific models, media, or contexts, and have not comprehensively synthesized the overall potential, challenges, and research trends of STEM-based biotechnology learning (Susanto & Hermina, 2024; Kusuma & Mendez., 2024).

Therefore, this study offers novelty by providing a comprehensive synthesis of recent research through a systematic literature review, focusing specifically on the integration of STEM approaches in biotechnology learning. This study not only identifies the potential and challenges but also highlights research gaps and future directions that have not been addressed in previous reviews.

Therefore, this study aims to analyze the potential of STEM-based biotechnology learning through a Systematic Literature Review (SLR). This study is expected to identify key trends, opportunities, and challenges in the implementation of STEM in biotechnology learning, as well as provide practical recommendations for improving biology education practices in Indonesia. In addition, this study seeks to contribute to the development of more contextual, innovative, and relevant learning strategies that align with the demands of 21st-century education.

2. Method

This study employed a Systematic Literature Review (SLR) approach to identify, evaluate, and synthesize previous research related to STEM-based biotechnology learning in biology education. The SLR method allows researchers to systematically collect and analyze existing studies in order to obtain comprehensive and reliable findings, as well as to identify research gaps within a particular field (Pradana et al., 2021; Munawwarah et al., 2024).

The literature search was conducted using the Publish or Perish application to retrieve relevant articles from academic databases such as Google Scholar, Scopus, and Web of Science. The search strategy used several keyword combinations, including "STEM-based learning," "biotechnology education," "biology STEM learning," and "STEM pedagogy." The search was limited to articles published within the last eight years (2017–2024) to ensure the relevance and recency of the data (Sari et al., 2024).

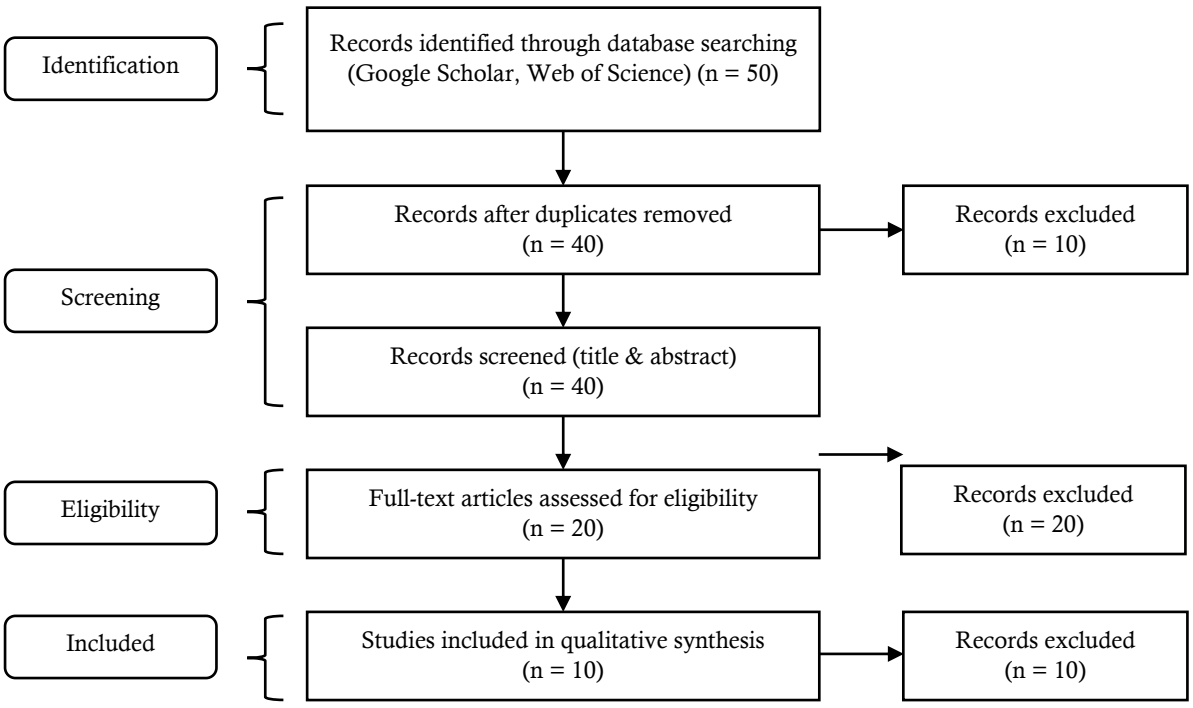

Figure 1. The literature selection process is explained using the PRISMA flowchart

The selection of articles followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. In the initial stage, a total of 50 articles were identified through the database search. These articles were then screened based on titles and abstracts to determine their relevance to the research topic. Articles that were not related to biotechnology

learning, STEM approaches, or biology education were excluded. In addition, duplicate publications and articles without full-text access were removed during the screening process.

After the initial screening, 20 articles remained for further evaluation. A full-text assessment was then conducted using predefined inclusion and exclusion criteria, which considered aspects such as topic relevance, publication type, accessibility, publication year, and research focus. Based on this evaluation, 10 articles met all eligibility criteria and were selected for in-depth analysis.

Table 1. Inclusion and exclusion criteria for article selection

Criteria	Inclusion Criteria	Exclusion Criteria
Topic relevance	Articles discussing STEM approaches in biotechnology or biology learning	Articles not related to STEM, biotechnology, or education
Publication type	Peer-reviewed journal articles	Conference abstracts, theses, dissertations, books, non-scientific publications
Language	Articles published in English or Indonesian	Articles published in other languages
Accessibility	Articles with full-text access available	Articles without full-text access
Publication year	Articles published between 2017–2025	Articles published before 2017
Research focus	Studies focusing on STEM-based learning, biotechnology education, or biology learning	Studies focusing only on technical/biological data without educational context

The inclusion criteria in this study consisted of: (1) articles discussing STEM approaches in biotechnology or biology learning, (2) peer-reviewed journal publications, (3) articles published in English or Indonesian, (4) publications within the last eight years, and (5) articles with full-text access. Meanwhile, the exclusion criteria included: (1) studies not related to education or biotechnology learning, (2) non-scientific publications such as theses, books, or reports, and (3) articles with incomplete or unclear data.

Table 2. Distribution of Selected Articles

No	Author	Journal	Index (Scopus/Sinta)
1	Ilma et al. (2023)	Pegem Journal of Education and Instruction	Scopus (Q2)
2	Laranjo et al. (2020)	Journal of STEM Education	Scopus (Q3)
3	Elladora et al. (2024)	International Journal of Learning, Teaching and Educational Research	Scopus (Q3)
4	Qurratu'ain et al. (2024)	Jurnal Penelitian Pendidikan IPA (JPPIPA)	Sinta 2, Google Scholar
5	Widiarti et al. (2022)	Jurnal Pendidikan Sains	Sinta 2
6	Subekti et al. (2018)	International Journal of STEM Education	Scopus (Q1)
7	Pambudi et al. (2024)	Jurnal Penelitian Pendidikan IPA (JPPIPA)	Sinta 2, Google Scholar
8	Nurwahyunani (2021)	Journal for the Education of Gifted Young Scientists	Scopus (Q2)
9	Siswati et al. (2024)	Jurnal Pendidikan IPA Indonesia	Scopus (Q2)
10	Putri et al. (2023)	Jurnal Penelitian Pendidikan IPA (JPPIPA)	Sinta 2, Google Scholar

The selected articles were analyzed using a qualitative descriptive approach through thematic analysis. The analysis focused on identifying key themes, patterns, and trends related to the potential, implementation, challenges, and opportunities of STEM-based biotechnology learning. The findings were then synthesized to provide a comprehensive understanding of the role of STEM in enhancing biology learning, as well as to generate recommendations for future educational practices.

3. Result and Discussion

This chapter presents the results of the analysis of the systematic literature review process conducted to uncover the potential of biology learning in STEM-based biotechnology materials. The analysis stage began with a literature search using the Publish or Perish application from scientific databases such as Google Scholar, Scopus, and Web of Science. In the initial stage, 50 articles were successfully identified based on relevant keywords, such as STEM-based learning, biotechnology education, and biology STEM integration. The articles were then filtered based on inclusion criteria, namely relevance to the topic of STEM-based biotechnology, publication in the last five years, and availability of sufficient data for analysis. From this screening process, 40 articles were excluded because they did not meet the criteria, such as duplication, irrelevant coverage, or only providing general discussions without focusing on the implementation of STEM learning in biotechnology.

Table 3. Summary of research characteristics of included studies

No.	Author	Title	Key Findings
1.	Ilma et al. (2023)	A Systematic Literature Review of STEM Education in Indonesia (2016-2021) : Contribution to Improving Skills in 21st Century Learning (2023)	In biotechnology material, this approach can be applied through project-based activities that encourage students to understand biotechnology concepts in depth, develop critical thinking skills, and solve problems through direct and contextual experience. This article also underlines that the development of STEM-based learning requires further research to integrate material more holistically, especially to prepare students to face the challenges of industry 4.0 and the global job market.
2.	Laranjo et al. (2020)	An Upper-Level Biology Course Designed to Develop Science Communication in STEM Majors by Examining the Biotechnology Industry (2020)	Specific to biotechnology, a STEM approach helps students understand the drug development process, biological aspects, and associated ethical dilemmas. This approach also integrates "soft skills" such as teamwork, problem solving, time management, and creativity, which are very relevant to prepare them to enter the STEM-based world of work.
3.	Elladora et al. (2024)	Challenges in Teaching Biotechnology in the Philippine STE Program (2024)	Identified five key barriers: mismatched teacher skills, overly abstract material, students' weak science foundations, a lack of innovative strategies, and inadequate laboratory facilities. Solutions require intensive teacher training, curriculum updates, and the provision of digital/physical resources to support hands-on learning.
4.	Qurratu'ain et al. (2024)	Classroom Students Collaborative Abilities XII SMA	Biotechnology is often considered difficult because of its complex nature, so a STEM-based approach is seen as a solution to make the material more relevant and

		Negeri 5 Surakarta in Learning Biotechnology PJBL Integrated STEM Teaching Year 2023/2024 (2024)	applicable. Biotechnology material covers applications ranging from fermentation to manipulation of recombinant DNA, which are relevant to modern technological developments.
5.	Widiarti et al. (2022)	Development STEM-Based Biotechnology Learning Tools to Practice Critical Thinking (2022)	The STEM approach in biotechnology material provides positive results in improving the quality of learning, especially in training students' critical thinking skills. The STEM approach helps students understand complex biotechnology applications in an engaging, interactive, and relevant way. This device facilitates student-centered learning, thereby increasing motivation and learning outcomes.
6.	Subekti et al. (2018)	Comparison of Student Achievement in Agricultural Biotechnology STEM Integrated Using Research Based Learning (2018)	The research results from this article show that the STEM (Science, Technology, Engineering, and Mathematics) approach has a significant opportunity to increase student learning achievement in biotechnology material. The integration of STEM in a biotechnology curriculum can help students develop critical, creative and collaborative thinking skills, which are critical in facing global challenges in the fields of science and technology.
7.	Pambudi et al. (2024)	Improving Creative Thinking Skill on Biotechnology Material Through The Effectiveness of Project Based Learning-STEM E-Module Provided with Formative Assessment (2024)	The PjBL-STEM approach to biotechnology material is more effective than conventional methods in improving students' creative thinking skills, especially on indicators of fluency, flexibility, originality and elaboration.
8.	Nurwahyunani (2021)	Literature review: a STEM approach to improving the quality of science learning in Indonesia (2021)	The STEM approach has been shown to improve learning motivation, literacy skills, and higher-order thinking skills (HOTS). STEM implementation can also connect science concepts to everyday life, provide hands-on experiences, and motivate students to pursue STEM careers. However, the success of this approach requires full support from stakeholders, including well-trained teachers and the availability of adequate learning resources.
9.	Siswati et al. (2024)	The Effectiveness of E-Module STEM Biotechnology to Empower Metacognitive Skills and Science Process Skills of High School Students with Low Academic Ability in Industrial Agriculture Areas (2024)	STEM approach through the use of E-Module on Biotechnology material has a great opportunity to improve students' metacognitive skills and science process skills, especially in the industrial agriculture area. STEM-based E-Module has been proven effective in providing interactive and engaging learning experiences, helping students with low academic abilities to understand the material more deeply.
10.	Putri et al. (2023)	The Influence of Problem Based Learning (PBL) Model Based on	STEM in biotechnology material has great potential to improve critical thinking skills, link biotechnology theory with real-world applications, STEM allows biotechnology learning to be more relevant and interesting through the

	STEM Approach on Critical Thinking Ability Phase-E in Biology Learning (2023)	use of technology, experiments, and collaboration in solving real problems, and compatibility with PBL.

The STEM (Science, Technology, Engineering, and Mathematics) approach in Biotechnology learning provides a significant contribution to improving the quality of education, especially in Biology learning. Based on the analysis of 10 relevant articles, this approach shows great potential to be applied in Biotechnology learning with various development opportunities. The following are the results of the discussion covering the potential and opportunities for implementing the STEM approach in biotechnology material.

The Potential of STEM Approaches to Biotechnology Materials

The application of the science, technology, engineering, and mathematics (STEM) approach to Biotechnology learning offers significant potential to improve the quality of learning and student learning outcomes (Pambayun & Shofiyah, 2023). This approach is not only oriented towards mastering theory but also emphasizes the development of skills that are relevant to the needs of the 21st century. Here are some important aspects related to the potential of the STEM approach in Biotechnology learning.

The STEM approach helps students develop critical thinking skills that are essential in understanding Biotechnology. The STEM approach directly contributes to the development of students' critical thinking skills, which are essential competencies in understanding and analyzing Biotechnology concepts (Selvina, 2024; Arifin & Sulistyo, 2023). Through activities based on problem solving, experiments, and simulations, students are invited to evaluate information in depth, identify patterns, and make decisions based on valid data. For example, students can analyze the impact of genetic engineering technology on the environment or society, so that they not only understand the theory but also learn to think critically about real issues related to Biotechnology (Romadhona et al. 2024; Nurwidodo et al. 2021).

Articles 5 and 10 highlight that STEM-based learning through the Problem-Based Learning (PBL) model and the development of learning tools can train students in analyzing real problems, such as microorganism-based biotechnology production. Students are invited to identify problems, find solutions, and develop in-depth arguments related to biotechnology topics, such as fermentation techniques or genetic engineering. The STEM approach develops critical thinking skills needed in science and technology. STEM-based biotechnology learning challenges students to think deeply about complex scientific concepts, such as genetic engineering, fermentation, or bioremediation. Project-based learning (PBL) in STEM gives students the opportunity to solve real-world problems using biotechnology knowledge (Suwandi, 2024; Kurniasih & Pratama., 2022).

STEM supports 21st century skills, including collaboration, communication, creativity, and problem solving. In STEM-based learning, students are trained to master 21st-century skills, such as collaboration, communication, creativity, and problem solving (Lafifa et al.2023; Schiff et al. 2025). The learning process often involves group projects that allow students to work together, discuss, and share ideas to achieve common goals. Students' creativity is also honed through challenges to design innovative solutions to Biotechnology problems, for example in creating more efficient biotechnology-based food production methods. Thus, STEM learning not only builds academic abilities, but also interpersonal skills that are crucial for the future (Fadillah,

2024; Stuppan et al., 2025). Articles 1 and 8 show that the integration of STEM in Biotechnology learning allows students to engage in team collaboration, develop innovation, and solve complex problems in an applicable manner.

Technology is a key element in the STEM approach to make Biotechnology learning more interesting and interactive. Technology is an integral element in the STEM approach that makes Biotechnology learning more interesting and interactive (Segal & Kalfon-Hakhmigari, 2025; Waty et al.2024). The use of digital media, such as virtual simulations, laboratory software, or augmented reality (AR), allows students to visualize complex processes, such as microorganism fermentation or DNA manipulation, directly. In addition, this interactive media also provides a deeper and more memorable learning experience, so that students can understand the material in a more effective and enjoyable way (Tohir et al.2024). Articles 7 and 9 demonstrate the effectiveness of using STEM-based E-Modules in enhancing students' understanding of Biotechnology. With virtual simulations and technology-based experiments, students can visualize biotechnology processes such as tissue culture or protein synthesis.

The STEM approach allows students to understand the relationship between Biotechnology theory and real-world applications. The STEM approach provides opportunities for students to connect theory with real applications in the workplace or society. Biotechnology learning is no longer limited to abstract concepts, but is also integrated with practical applications, such as the use of biotechnology in the production of medicines, renewable energy, or waste management (Yoshinaga et al., 2026; Nurjanah et al. 2024). With this contextualization, students are able to see the relevance of the material they are learning to everyday life and global challenges, such as climate change or food security. This not only strengthens their conceptual understanding but also motivates them to contribute to solving these problems in the future (Siregar et al., 2024). Article 2 shows that STEM-based learning in Biotechnology helps students explore industrial applications, such as the production of biofuels, enzymes, or pharmaceuticals, so that the relevance of the material to real life becomes more pronounced.

Opportunities for Implementing the STEM Approach to Biotechnology Materials

The Science, Technology, Engineering, and Mathematics (STEM) approach has great potential to be applied in Biotechnology learning. With the various advantages offered, this approach can improve the quality of learning, foster student interest, and strengthen the relevance between science and real life. The following are the main opportunities in applying the STEM approach to Biotechnology material (Davidi et al.2021).

The STEM approach is very suitable to be applied in project-based learning that emphasizes experimentation and collaboration. The STEM approach is ideal for implementation through a project-based learning model or Project-Based Learning (PjBL). This model emphasizes exploration, experimentation, and student collaboration in completing a relevant project. In the context of Biotechnology, students can develop projects such as enzyme production using microorganisms, analysis of the impact of biotechnology on the environment, or design solutions to improve the efficiency of biotechnology-based agriculture (Prasetiyani, 2024; Rahmawati & Suryadi., 2018). Through this approach, students not only learn concepts but also apply them in real situations, so that learning becomes more meaningful and challenging. Articles 4, 7, and 9 reveal that PjBL-STEM provides students with the opportunity to conduct hands-on research, such as fermentation in making tape or tempeh, as well as enzyme testing.

STEM allows a flexible approach for students with different academic abilities. The STEM approach offers flexibility that allows it to be applied at various academic levels, from elementary

school to college. For students with lower levels of understanding, Biotechnology material can be simplified by using STEM-based exploration and game approaches (Tambunan et al. 2024; Halim & Kurniawan., 2020). At higher levels, learning can focus on in-depth research or complex projects that require critical and creative thinking. With this flexibility, the STEM approach can be tailored to meet the diverse needs and academic abilities of students (Ismail et al.2024). Article 9 shows that the STEM E-Module is effective in helping students with low abilities to stay engaged in learning and improve their understanding of Biotechnology concepts.

The use of STEM-based learning modules allows teachers to create more interesting and applicable materials. The STEM approach also encourages teachers to develop more innovative and applicable teaching materials. For example, STEM-based learning modules can include biotechnology process simulations, the use of interactive digital media, or virtual experiments (Segal & Kalfon-Hakhmigari, 2025; Sirait & Manurung, 2020). This kind of teaching material not only helps students understand the concept of Biotechnology more deeply but also makes learning more interesting and relevant. In addition, this approach allows the integration of technologies such as augmented reality (AR) to visually show the fermentation process or genetic manipulation (Rinarto, 2023). Articles 5 and 7 propose the development of interactive teaching materials that utilize technology to support Biotechnology learning, such as digital modules equipped with simulations or virtual experiments.

Biotechnology is one of the branches of science that is relevant to STEM careers. Biotechnology is one of the branches of science that has high relevance to STEM-based careers. By introducing Biotechnology concepts through a STEM approach, students can see various interesting career opportunities, such as in genetic engineering, food technology, drug development, or renewable energy. This not only increases students' interest in learning Biotechnology but also prepares them to enter the workforce that requires STEM skills (Iscan, 2025; Sirait & Manurung, 2020). Article 6 shows that STEM-based Biotechnology learning can motivate students to pursue careers in technological innovation, such as agriculture, pharmaceuticals, or bioengineering.

STEM integration in the Biotechnology curriculum requires teacher training and the development of relevant curricula. Implementation of the STEM approach in Biotechnology learning requires support from various parties, especially in improving teacher competency and developing relevant curricula. Teachers need to be trained to master the STEM approach, including in the use of technology and management of STEM-based projects (Thomas et al. 2026). In addition, the curriculum must be designed to be able to integrate Biotechnology materials with STEM principles systematically. With this training and curriculum development, STEM-based Biotechnology learning can be implemented effectively and provide a significant positive impact (Diniz et al., 2025). Articles 1, 3, and 8 highlight the need to adjust the national curriculum so that STEM can be integrated with Biotechnology materials, so that it is relevant to global challenges.

4. Conclusion

This study concludes that STEM-based biotechnology learning has significant potential to enhance the quality of biology education by improving students' conceptual understanding, critical thinking, and engagement. The integration of interdisciplinary knowledge and contextual learning makes biotechnology more relevant and meaningful for students. However, several challenges remain, including limited infrastructure, lack of teacher readiness, and insufficient teaching materials. Therefore, it is recommended that policymakers support the integration of

STEM in the biology curriculum through structured programs and resource allocation. Teachers should be provided with professional development and training to effectively implement STEM-based learning. Future research is also needed to develop innovative teaching materials and explore the effectiveness of STEM approaches in diverse educational contexts. These efforts are essential to ensure the successful implementation of STEM-based biotechnology learning in Indonesia.

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