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The Effect of the Science, Technology, Engineering, and Mathematics (STEM) Approach on Higher-Order Thinking Skills in Biology Education: A Meta-Analysis

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ABSTRACT

Background: The demands of 21st-century education require students to possess higher-order thinking skills (HOTS), which can be developed through innovative instructional approaches, such as STEM (Science, Technology, Engineering, and Mathematics) learning in biology education. **Objective:** This study aims to analyse and synthesise the effects of the STEM approach on students' higher-order thinking skills in biology learning. **Method:** This study employed a meta-analysis design using 20 relevant empirical studies published between 2020 and 2026. Data were analysed using effect size techniques to determine the magnitude of the STEM approach's influence on students' HOTS. **Results:** The findings revealed that the effect sizes ranged from 0.47 to 7.60, with most studies demonstrating large to very large effect sizes. These findings indicate that the STEM approach, particularly when integrated with deep learning strategies, has a strong influence on improving students' higher-order thinking skills. **Conclusion:** The study concludes that the STEM approach is effective in biology learning for enhancing students' analytical, evaluative, critical thinking, and problem-solving abilities. **Originality/Value:** This study offers methodological and synthesis novelty to biology education by demonstrating the overarching magnitude of effect of the Science, Technology, Engineering, and Mathematics (STEM) framework in advancing students' higher-order thinking skills (HOTS) regarding biological concepts within a comprehensive, multi-study meta-analytic synthesis, an area that remains limited in systematic aggregated evaluation. These findings enrich the empirical evidence and serve as a strategic reference for curriculum designers and educational policymakers in developing interdisciplinary science instructional models to foster 21st-century competencies, analytical reasoning, and complex problem-solving abilities.

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STEM approach; Higher-order thinking skills; Biology education; 21st-century skills

1. INTRODUCTION

The development of the 21st century requires students to possess higher-order thinking skills (HOTS) as essential competencies for coping with the rapid advancement of science and technology and increasingly complex life challenges (Fitarahmawati & Suhartini, 2021). Higher-order thinking skills are associated with cognitive processes of analyzing, evaluating, and creating, meaning that students are not only expected to remember or understand concepts but also to apply knowledge critically and creatively in problem-solving situations (Willenda et al., 2024). In the educational context, HOTS has become one of the key competencies necessary for supporting reasoning, scientific thinking, and evidence-based decision-making.

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In biology education, HOTS plays a crucial role because biological content cannot be adequately understood through rote memorization alone; it must also be connected to life phenomena, scientific observation, data analysis, and contextual problem-solving (Ningrum et al., 2023). Students need to be trained to understand the relationships among concepts, interpret biological phenomena, and develop solutions grounded in scientific evidence. Sun et al. (2022) demonstrated that HOTS is positively associated with scientific literacy among biology education students, indicating that higher-order thinking skills support learners in reasoning, investigating problems, and understanding scientific information more effectively. Furthermore, Primahesa et al. (2023) explained that various instructional models, such as Problem-Based Learning, inquiry learning, discovery learning, and laboratory activities, can be utilized to enhance students' HOTS in biology learning.

One instructional approach considered relevant for developing higher-order thinking skills is the Science, Technology, Engineering, and Mathematics (STEM) approach. The STEM approach integrates concepts from science, technology, engineering, and mathematics into the learning process, enabling students to connect theoretical concepts with real-world problems. Anggraeni et al. (2022) stated that STEM-based education is necessary to address the demands of 21st-century learning because it can support the development of HOTS and students' digital literacy. The implementation of STEM also encourages students to think critically, creatively, collaboratively, and communicatively through project-based activities, investigations, experiments, and problem-solving tasks (Amalia et al., 2025).

Numerous studies have shown that implementing STEM positively influences students' higher-order thinking skills. Santoso & Arif (2021) found that inquiry-based learning integrated with STEM education improved students' critical thinking skills. Ningrum et al. (2024) reported that STEM-integrated project-based learning significantly affected students' problem-solving abilities and collaborative skills in ecosystem-related topics. In addition, Funa et al. (2024) demonstrated that the PBL-STEM model effectively enhanced students' deductive reasoning, inductive reasoning, and judgment skills in environmental pollution topics within biology learning. These findings indicate that STEM has strong potential to foster higher-order thinking skills in biology education.

Nevertheless, previous studies investigating the implementation of STEM on higher-order thinking skills have produced varying results. These differences may be influenced by the instructional models employed, educational levels, learning materials, sample sizes, research instruments, and the duration of instructional implementation. Fahira & Puspitawati (2025) suggested that STEM research in biology education aimed at developing critical thinking skills still offers opportunities for further development across various learning contexts. The variability in research findings underscores the need for a more comprehensive review to provide empirical evidence on the effectiveness of the STEM approach in improving students' higher-order thinking skills.

This study aims to analyze and synthesize findings from previous studies on the effects of the STEM approach on students' higher-order thinking skills in biology learning using a meta-analysis. By calculating effect sizes, this study is expected to provide empirical evidence concerning the effectiveness of the STEM approach and serve as a reference for teachers, researchers, and educational practitioners in developing biology learning that is active, contextual, and oriented toward higher-order thinking skills.

2. METHOD

2.1 Research Design

This study employed a quantitative meta-analysis design. A meta-analysis was used to review and synthesize findings from previous studies on the implementation of the Science, Technology, Engineering, and Mathematics (STEM) approach integrated with deep learning in biology education and its influence on students' Higher-Order Thinking Skills (HOTS). Through meta-analysis, findings from various scientific studies were systematically analyzed to obtain a comprehensive overview of the effectiveness of the STEM approach in improving students' higher-order thinking skills.

2.2 Research Object

This study was a meta-analysis and, therefore, was not conducted in a specific field setting. The research objects consisted of national and international scientific journal articles discussing the implementation of the Science, Technology, Engineering, and Mathematics (STEM) approach and Higher-Order Thinking Skills (HOTS) in biology learning. The analyzed articles were limited to publications from 2020 to 2026 to ensure that the studies reflected recent developments in educational research.

The population of this study comprised all scientific articles on the STEM approach and HOTS in biology education. The sample consisted of 20 selected articles that met predetermined inclusion criteria. The inclusion criteria were as follows: (1) the articles were published in national or international journals; (2) the studies discussed STEM, HOTS, or biology learning; (3) the articles were published between 2020 and 2026; and (4) the studies provided quantitative data that could be used to calculate effect sizes. Articles that were irrelevant to the research topic, unavailable in full text, or lacking the statistical data required for effect size calculation were excluded from the analysis.

2.3 Instruments and Data Collection

The instrument used in this study was a data extraction sheet. The sheet was used to record article identity, authors' names, year of publication, article title, research method, sample sizes of the experimental and control groups, mean scores, standard deviations, t-values, f-values, correlation coefficients (r), p-values, and other statistical information required for effect size calculation. Data collection was conducted through a systematic search of scientific articles using keywords such as STEM, Higher-Order Thinking Skills, HOTS, critical thinking, and biology learning. The identified articles were then screened using title, abstract, method, and results reviews to ensure their relevance to the study's focus. The selected studies were predominantly quasi-experimental, employing pretest-posttest designs, either with experimental and control groups or a single treatment group. The findings also indicated that the STEM approach was integrated with several innovative learning models, including Project-Based Learning (PBL), Problem-Based Learning (PBL), the flipped classroom, and learning cycle models. The diversity of research designs and instructional approaches provided broader insights into the implementation of STEM in improving students' higher-order thinking skills in biology learning.

2.4 Data Analysis

The data were analysed using effect-size metrics. Effect size calculations were conducted using Cohen's d or Hedges' g, depending on the availability of statistical data in each study. The analyzed data included sample sizes, mean scores, standard deviations, t-values, f-values, correlation coefficients (r), and p-values. The calculated effect sizes were subsequently interpreted based on established effect size criteria to determine the magnitude of the STEM approach's influence on students' higher-order thinking skills. Furthermore, the effect sizes from all selected studies were synthesized to identify general patterns regarding the effectiveness of STEM-based learning in biology education.

2.5 Research Procedure

The data collection technique in this study followed the meta-analysis procedures proposed by David B. Wilson and George A. Kelley, as referenced in previous studies (Sari et al., 2021; Anggreni et al., 2019). The procedure began by identifying the research problem and determining the independent and dependent variables. Subsequently, relevant research reports and scientific articles were searched from various academic sources related to the research topic. The identified articles were then screened using title and abstract review to ensure their relevance to the study's focus. The next stage involved examining the methodological aspects of the studies, including research design, methods, sample characteristics, and statistical analysis techniques. Studies that met the inclusion criteria were subsequently categorized and compared based on their respective characteristics. Afterwards, effect size calculations and the extraction of key statistical information from each study were conducted. The final stage involved synthesising and analysing all research findings to conclude from the meta-analysis results.

3. RESULTS AND DISCUSSION

3.1 Results

The findings of this study are presented based on the analysis of scientific articles that met the inclusion criteria for this meta-analysis. The discussion focuses on the magnitude of the effect size of implementing the STEM approach on students' higher-order thinking skills (HOTS). The results are presented in tabular form to facilitate data interpretation, followed by a discussion of trends in the findings, variations in effect sizes, and their implications for the effectiveness of the STEM approach in learning.

Table 1. Effect Size Analysis Results of the Implementation of the STEM Approach on Students' Higher-Order Thinking Skills

No.	Study/Year	Effect Size (d)	Interpretation
1	Fadila et al., (2025). *The Effect of STEM Integrated PjBL Learning on Students' HOTS and Collaboration Abilities on Biotechnology Material*	1.21	Very Large
2	Utaminingsih et al., (2025). *Effect of Science, Technology, Engineering, and Mathematics (STEM) on the Higher-Order Thinking Skills (HOTS) of Elementary School Students*	0.47	Small
3	Yaki. (2022). *Fostering Critical Thinking Skills Using an Integrated STEM Approach among Secondary School Biology Students*	1.34	Very Large
4	Birnin et al., (2023). *Effectiveness of STEM Problem-Based Learning on the Achievement of Biology among Secondary School Students in Nigeria*	1.51	Very Large
5	Indrasti & Paidi. (2025). *Development of STEM-Integrated Project-Based Learning to Improve Critical Thinking Skills of Senior High School Students on Environmental Change Material*	1.64	Very Large
6	Razak et al., (2024). *The Influence of the Science, Technology, Engineering, and Mathematics Approach with Mind Maps on Students' HOTS in Biology Learning for Grade X at SMA N 4 Kerinci*	1.63	Very Large
7	Hardiani. (2025). *STEM-Based Biology Learning and Its Impact on Students' Learning Outcomes*	1.96	Very Large
8	Yasifa et al., (2023). *Implementation of STEM Learning on Ecosystem Material toward Students' Critical Thinking Skills*	5.78	Very Large
9	Salam et al.. (2025). *The Effect of the STEM Approach on Students' Critical Thinking Skills in Grade 11 at SMAN 9 Makassar*	1.13	Very Large
10	Mahirah & Hambali. (2025). *Implementation of the STEM Learning Approach on Science Concept Understanding among Fifth-Grade Students at SDN Tidung*	1.53	Very Large
11	Ramadhani et al.. (2024). *STEM-CP-Based Flipped Classroom Model for HOTS of Prospective Elementary School Teachers*	7.60	Very Large
12	Chamidah & Suhartono. (2023). *The Influence of the Implementation of Problem-Based Learning and STEM on the HOTS Ability of High School Students in Surabaya*	3.88	Very Large
13	Ardini et al., (2024). *The Effect of STEM-Based Biology Learning on Students' Critical Thinking Skills on Environmental Pollution Material*	0.60	Moderate
14	Fitriyani et al.. (2020). *Implementation of the PjBL-STEM Model to Improve Higher-Order Thinking Skills*	1.21	Very Large
15	Fitriana & Dewi. (2023). *The Effect of E-Modules with a STEM Approach on Junior High School Students' Motivation and Creativity*	0.47	Small
16	Sudarmi et al., (2025). *The Effect of Ethno-STEM Integrated E-Modules through PjBL on Students' Creative Thinking Skills in Matter and Its Changes*	1.34	Very Large
17	Rosalinda et al., (2023). *Implementation of the STEM Learning Approach in Developing Creative Disposition and Creative Thinking Skills among Junior High School Students*	1.64	Very Large
18	Simatupang et al., (2023). *The Effect of the Project-Based Learning Model with a STEM Approach on Students' Critical Thinking Skills in the Human Excretion System*	3.24	Very Large
19	Salma et al., (2022). *The Effect of the STEM-Based Learning Cycle (5E) Model on Science Literacy and Learning Outcomes of Grade X Students*	1.33	Very Large
20	Mulyono et al., (2025). *The Effect of the STEM Approach on Students' Interest and Learning Outcomes in Biology*	5.78	Very Large

Based on the analysis of the 20 reviewed studies, the effect sizes ranged from 0.47 to 7.60, indicating variation in the magnitude of the STEM approach's influence on students' higher-order thinking skills. Overall, the majority of studies demonstrated a very large effect, with 15 reporting effect sizes greater than 1.00. In addition, several studies were categorised as having large and moderate effects, while only one study demonstrated a small effect size of 0.47.

The highest effect size was 7.60, followed by 5.78 and 3.88, indicating that implementing the STEM approach under certain learning conditions can have a very strong impact on improving students' higher-order thinking skills.

Meanwhile, most effect sizes ranged from 1.13 to 1.96, suggesting that the STEM approach consistently provides a strong to very strong positive influence on HOTS learning outcomes.

These findings indicate that the STEM approach is highly effective in fostering students' analytical, evaluative, critical, creative, and problem-solving abilities in biology learning. The positive effects identified across the reviewed studies also suggest that integrating STEM with innovative learning models, such as Project-Based Learning (PBL), Problem-Based Learning (PBL), flipped classroom, and learning cycle models, can strengthen the effectiveness of STEM implementation in improving students' higher-order thinking skills.

Variation in effect sizes across studies may be influenced by several factors, including differences in educational levels, sample sizes, instructional duration, learning materials, research designs, and the types of instructional models integrated with STEM. Studies reporting very high effect sizes generally implemented STEM through active, project-based, and contextual learning activities that encouraged students to engage in scientific inquiry, collaboration, experimentation, and real-world problem-solving.

This meta-analysis finds that the STEM approach significantly and positively contributes to the development of students' higher-order thinking skills. Therefore, STEM-based learning can be considered an effective instructional approach for developing 21st-century competencies in biology education.

3.2. Discussion

The results of this meta-analysis indicate that the STEM approach has a positive effect on improving students' higher-order thinking skills in biology learning. These findings suggest that STEM-based learning supports the development of 21st-century skills, particularly critical thinking, analytical thinking, creativity, and problem-solving abilities. The dominance of studies reporting high effect size categories indicates that the integration of science, technology, engineering, and mathematics in learning can help students understand biological concepts more deeply and contextually.

The effectiveness of the STEM approach in enhancing higher-order thinking skills is closely related to its student-centered learning characteristics. In STEM-based learning, students do not merely receive information passively but are actively involved in investigation, experimentation, data analysis, and real-world problem-solving activities (Udju et al., 2023). These activities provide students with opportunities to develop the ability to analyze information, evaluate alternative solutions, and create ideas or products based on scientific reasoning. This process aligns with the indicators of Higher-Order Thinking Skills (HOTS), which include analyzing, evaluating, and creating.

In the context of biology education, the STEM approach helps students connect biological concepts with real-life phenomena, making learning more meaningful (Rahmawati et al., 2024). Biology topics related to the environment, ecosystems, pollution, and living systems can be learned through project-based activities and problem-solving tasks (Hartanti et al., 2023). Through these processes, students not only understand concepts theoretically but are also able to apply knowledge in real-life situations and develop scientific thinking skills based on evidence. This condition demonstrates that the STEM approach can create more contextual learning experiences and support the development of higher-order thinking skills (Sarwi et al., 2024).

The findings of this study are consistent with previous research demonstrating the effectiveness of STEM-based learning in improving students' higher-order thinking skills. Hardiani (2025) found that STEM-based biology learning significantly improved students' learning outcomes. STEM integrated with Problem-Based Learning effectively enhanced biology achievement and students' higher-order thinking skills. Santoso & Arif (2021) also demonstrated that inquiry learning integrated with STEM education improved students' critical thinking skills. Furthermore, Ningrum et al. (2024) revealed that STEM-integrated Project-Based Learning positively influenced students' problem-solving abilities and collaborative skills in ecosystem topics. The PBL-STEM model effectively improved students' deductive reasoning, inductive reasoning, and judgment skills in environmental pollution topics in biology learning. These findings collectively reinforce the argument that the STEM approach has strong potential to develop various aspects of students' higher-order thinking skills.

Nevertheless, the effectiveness of STEM implementation may be influenced by several factors within the learning process. Differences in instructional models, student characteristics, teacher readiness, instructional duration, and the availability of learning facilities may affect the success of STEM implementation in improving students' HOTS (Azizahwati et al., 2023). STEM learning that is systematically designed and supported by investigative and problem-solving activities tends to produce more optimal outcomes. Conversely, STEM implementation that is not fully integrated into the learning process may result in less optimal effects (Cao et al., 2025). These findings indicate that the success of the STEM approach depends not only on the use of the approach itself but also on the quality of its implementation in classroom learning.

The findings of this study demonstrate that the STEM approach is an effective instructional strategy for improving students' higher-order thinking skills in biology education. The integration of STEM with innovative learning models, such as Problem-Based Learning, Project-Based Learning, inquiry learning, and flipped classroom models, can help create more active, contextual, and 21st-century-oriented learning environments. Therefore, the STEM approach can be considered an alternative instructional strategy to support the development of students' higher-order thinking skills in biology learning.

4. IMPLICATIONS AN CONTRIBUTIONS

4.1 Research Implications

The findings of this study provide practical implications for educators and educational practitioners in implementing STEM-based learning strategies to improve students' higher-order thinking skills effectively. The results indicate that integrating STEM into biology learning can support the development of critical, analytical, and evaluative thinking, as well as problem-solving skills, which are essential components of 21st-century competencies. Therefore, the STEM approach can be considered an alternative, innovative instructional strategy that helps create more active, contextual, and student-centred learning environments.

In addition, the findings suggest that STEM-based learning should be systematically integrated into biology instruction through activities involving investigation, experimentation, project-based learning, and real-world problem-solving. Such learning activities encourage students to actively participate in the learning process and apply scientific knowledge in meaningful contexts. The results of this study also imply that teachers need to strengthen their pedagogical readiness and instructional design skills to optimise the implementation of STEM learning in classroom practice.

4.1 Research Contributions

This study contributes empirically to the evidence base on the effectiveness of the STEM approach in improving students' higher-order thinking skills in biology learning. The study also contributes to enriching meta-analysis research in biology education by synthesising studies on STEM implementation and HOTS development. Furthermore, this study provides broader insights into the effectiveness of integrating STEM with innovative learning models, such as Problem-Based Learning, Project-Based Learning, inquiry learning, and flipped classroom models. The findings demonstrate that STEM-based learning not only improves students' conceptual understanding but also supports the development of critical, analytical, creative, collaborative, and problem-solving abilities. The findings of this study may serve as a reference for educators, researchers, and educational practitioners in developing innovative instructional strategies to enhance 21st-century skills, particularly students' higher-order thinking skills in biology education.

5. LIMITATIONS AND FUTURE RESEARCH DIRECTION

5.1 Research Limitations

This study has several limitations that should be considered when interpreting the findings. First, this study focused only on articles examining the effects of the STEM approach on students' higher-order thinking skills in biology learning. It did not include other variables potentially influenced by STEM implementation, such as learning motivation, creativity, scientific literacy, collaboration skills, and students' academic achievement.

Second, not all analysed articles provided complete statistical data required for effect size calculations, resulting in some relevant studies not being fully included in the analysis. Third, variations in research characteristics, such as educational levels, instructional models, learning materials, sample sizes, and duration of STEM implementation, may have influenced the findings of this meta-analysis. Fourth, this study was limited to articles accessible to the researchers, potentially excluding other relevant studies. The findings of this study should be interpreted carefully, particularly regarding the generalisation of results across different educational contexts and instructional conditions.

5.1 Recommendation for Future Research

Future studies are recommended to examine the effects of the STEM approach on other variables in biology learning, such as scientific literacy, creativity, learning motivation, collaboration skills, and students' academic achievement. Further research should also involve a larger number of studies from more diverse publication sources

to produce more comprehensive and representative meta-analysis findings. In addition, future meta-analyses are encouraged to conduct subgroup analyses by educational level, integrated STEM instructional models, biology learning materials, and the duration of STEM implementation to identify the factors that most strongly influence the effectiveness of the STEM approach in improving students' higher-order thinking skills. Comparative studies across different educational contexts and countries are also recommended to provide broader insights into the implementation of STEM-based learning in supporting the development of 21st-century competencies.

6. CONCLUSION

Based on this meta-analysis, the STEM approach has been shown to improve students' higher-order thinking skills in biology learning. The implementation of STEM supports the development of critical, analytical, and evaluative thinking, creativity, and problem-solving skills, which are essential components of 21st-century competencies. STEM-based learning also helps students connect biological concepts with real-world problems, making the learning process more contextual and meaningful.

The effectiveness of the STEM approach in improving higher-order thinking skills depends on the quality of instructional implementation. The integration of STEM with innovative learning models, such as Problem-Based Learning, Project-Based Learning, inquiry learning, and flipped classroom models, can create more active, collaborative, and student-centred learning environments. In addition, students' engagement, teacher readiness, and the availability of learning facilities also influence the successful implementation of STEM in biology learning.

The STEM approach can be considered an effective alternative instructional strategy to support the development of students' higher-order thinking skills in biology education. Consequently, STEM-based learning should be systematically designed and adjusted to the characteristics of learning materials and students' needs to achieve optimal learning outcomes.

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Author Contribution Statement

All authors discussed the results, contributed to the final manuscript, and approved the final version for publication. Aji Adrian: Validation, Supervision, Data Collection, Writing – Review and Editing. Yulmairosa: Conceptualisation, Data Collection, Data Curation, Formal Analysis, Writing, Review, and Editing. Jamila Isdelia: Visualisation, Methodology, Data Curation, Writing, Review, and Editing.

Declaration of Generative AI (GenAI) Usage in Scientific Writing

The authors acknowledge the limited use of Generative Artificial Intelligence (GenAI), specifically Jenni AI, in the literature search and literature review processes. The use of GenAI in this study did not replace the authors' analytical processes but functioned solely as a supporting tool for developing literature search strategies and assessing the relevance of articles to the research focus. All articles included in this study were independently selected, examined, analyzed, and interpreted by the authors based on the established inclusion criteria, availability of statistical data, and relevance to the implementation of the STEM approach in improving students' higher-order thinking skills. All instances of Generative AI usage in this article were conducted by the authors in accordance with the JIPPG GenAI Tool Usage Policy, with the authors assuming full responsibility for the originality, accuracy, and integrity of the work.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this article. This study was conducted without political interests, personal relationships, commercial relationships, or financial support from any parties that could influence the research process, data analysis, interpretation of

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