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The Impact of STEM Education on Critical Thinking Skills: A Systematic Literature Review

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Abstract: This study aims to systematically examine and synthesize empirical evidence on the impact of Science, Technology, Engineering, and Mathematics (STEM) education on students' critical thinking skills. A systematic literature review (SLR) was conducted following the PRISMA protocol by initially identifying 200 relevant articles from reputable databases, including Scopus, ERIC, and Google Scholar. Through a rigorous screening and eligibility process, 10 peer-reviewed studies published between 2015 and 2025 were selected for in-depth analysis. The results indicate that STEM-based learning consistently enhances students' critical thinking skills, particularly through project-based learning, problem-based learning, and inquiry-based instructional approaches. The discussion highlights that the effectiveness of STEM education is strongly influenced by the quality of learning design, interdisciplinary integration, engineering design activities, and the use of higher-order thinking assessments. Differences in implementation quality, teacher competence, and learning contexts contribute to variations in outcomes. In conclusion, STEM education is an effective pedagogical approach for developing students' critical thinking skills; however, its success depends on well-structured implementation and adequate teacher preparedness to support 21st-century learning demands.

Keywords: Critical thinking skills; STEM education; Systematic literature review

Introduction

The challenges of the 21st century demand that students possess higher-order thinking skills, among which critical thinking is a fundamental competency for lifelong learning and success in a knowledge-based society. Critical thinking enables learners to analyse, evaluate, and synthesise information in order to solve complex problems and make reasoned decisions in an increasingly dynamic and information-rich world (Lai, 2020). In the context of science education, the cultivation of critical thinking is not only essential for academic achievement but also for developing scientific literacy and responsible citizenship, as students are expected to interpret scientific information, evaluate evidence, and make informed decisions related to societal and environmental issues.

In response to these demands, Science, Technology, Engineering, and Mathematics (STEM) education has emerged as a transformative pedagogical approach that integrates multiple disciplines to promote meaningful learning experiences. STEM education emphasises inquiry-based and problem-oriented learning, encouraging students to apply scientific concepts and engineering design processes to real-world issues (Bybee, 2020). Through hands-on experimentation, modelling, and interdisciplinary projects, STEM learning environments provide authentic contexts that foster reasoning, creativity, collaboration, and reflective judgement—core components of critical thinking.

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A growing body of research has demonstrated that STEM-based instruction has significant potential to enhance students' critical thinking skills (Becker & Park, 2019; Margot & Kettler, 2019). STEM learning that incorporates problem-based or project-based approaches has been shown to improve students' ability to evaluate evidence, design solutions, and justify arguments logically. Empirical studies conducted in Indonesia further support these findings. Oktavia and Ridlo (2020) reported that a project-based STEM approach improved elementary students' critical thinking through strengthened communication skills, while Rizqiyana et al. (2022) found that a thematic-media STEM approach was effective in developing critical thinking at the primary education level.

From a theoretical perspective, the relationship between STEM education and critical thinking is strongly grounded in constructivist learning theory, which posits that learners actively construct knowledge through interaction, inquiry, and problem-solving rather than passive reception (Piaget, 1973; Vygotsky, 1978). STEM learning environments reflect this paradigm by engaging students in authentic tasks that require questioning, reasoning, and reflection. In addition, Bloom's revised taxonomy identifies analysing, evaluating, and creating as higher-order cognitive processes, which are central to STEM-based learning activities, particularly those involving problem-based and project-based learning models (Anderson & Krathwohl, 2001). Furthermore, experiential learning theory (Kolb, 1984) suggests that meaningful learning occurs through cycles of concrete experience, reflection, conceptualisation, and experimentation—processes that are inherently embedded in STEM instruction, especially through engineering design and inquiry-based activities.

Despite strong theoretical foundations and promising empirical evidence, variations remain regarding how and to what extent STEM learning contributes to the development of critical thinking skills. Differences in educational levels, instructional models, teacher competencies, learning contexts, and assessment approaches may influence the effectiveness of STEM integration. For example, a quasi-experimental study at the junior high school level demonstrated significant gains in students' critical thinking through a STEM-based inquiry learning package (Isdianti et al., 2021), while a study in senior high school chemistry reported that a STEM learning model improved students' critical thinking skills in redox reaction topics (Gusman et al., 2023). These findings indicate that while STEM education is generally beneficial, its impact is context-dependent and influenced by specific instructional designs and implementation conditions.

Furthermore, although numerous empirical studies have been conducted in recent years, there remains a need for a comprehensive synthesis of evidence to clarify the mechanisms and conditions under which STEM education most effectively fosters critical thinking skills. A recent systematic review reported a marked increase in publications on STEM and critical thinking since 2018 and highlighted that educational level and the use of Problem-Based Learning (PBL) models are key factors influencing effectiveness (Ekayanti et al., 2025). However, existing reviews often focus on limited educational levels or specific disciplines, leaving gaps in understanding broader patterns, effective strategies, and contextual influences across diverse learning settings.

Therefore, this study is conducted to address these gaps by systematically analysing and synthesising existing literature on how STEM-based learning designs promote critical thinking skills among students from elementary to tertiary education levels. This review focuses on identifying effective instructional strategies, learning environments, and assessment approaches that support the development of critical thinking within STEM education. By integrating empirical findings with established learning theories, this study aims to provide a comprehensive and evidence-based foundation to inform educators, curriculum developers, and policymakers in designing innovative STEM learning models that effectively prepare students to meet the complex cognitive demands of the 21st century.

Method

The literature review sought to perform a systematic literature search in relation to STEM education and critical thinking skills. The following steps (Figure 1) were taken to conduct the systematic literature search: a research question was defined to set the scope of selected literature, and the inclusion and exclusion criteria were outlined clearly; an organized search strategy was adopted, focusing on terms chosen based on the research question and inclusion criteria; the search strategy was adapted to different databases; a period of time to conduct the search was agreed upon, premised on the search strategy and title of the paper; employing a wide range of databases based on similar publications increased the ease of using many different sources for analysis; details in the research methodology were designed to encourage transparency and credibility for any studies selected; discussing what could be done to check the abstracts relevant to the inclusion criteria was valuable in validating the worth of studies selected; the importance of a structured search strategy consistent with the breadth of the review was emphasized to cover a wide range of relevant studies in the existing literature; and conducting a systematic data extraction was important in providing a transparent approach, as any other team of researchers could replicate the search strategy and justify why the limits of the search were decided upon.

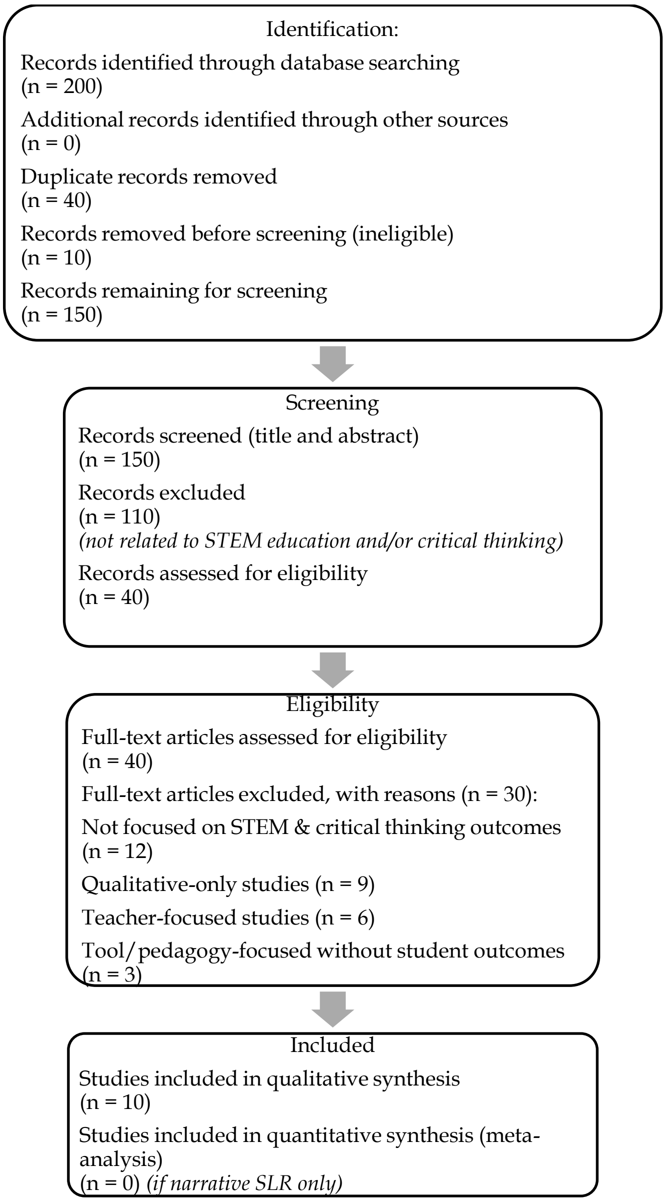

Figure 1. Research workflow

The final number of studies and gray literature identified and selected for full-text review was included in the analysis. These papers were chosen to observe whether the impact of STEM education on critical thinking skills could be observed. Appraisal of the included studies showed that while challenging, critically appraising the included studies was beneficial in ensuring the strength of the findings. The process of reviewing abstracts to identify papers was long and at times challenging. The search terms used did not always bring up the papers that a critical thinking researcher might expect, and limits of database searches had to be tested to be reassured that overlap and important papers were not missed. Despite this, the review was rigorous and thorough, and the findings are of a strong level.

Search Strategy

A systematic electronic search of four libraries was conducted. These databases were chosen based on their relevance to the field of education and for their inclusion of specific publication type filters relating to academic articles, book chapters, and conference proceedings. As prescribed by recommended best practices, key stems and synonyms representing the intervention and outcome terms were generated and systematically combined, with different searches completed on the basis of the title and abstract, and title, abstract, and keywords. The use of synonyms and search limitations was refined iteratively in consultation with the involved research librarian. The use of many varied synonyms and truncations ensured that a wide array of titles, abstracts, or keywords were potentially reached through each search, which is particularly valuable when a topic has many perspectives. Correlations between each search were conducted to ensure comprehensive coverage, with a large number of results returned for each search.

In order to embrace discourses from various disciplines, the search strategy has not been restricted to particular fields of study. The keywords, as well as the relevant terms from literature on literature, mathematics, engineering, and technology, were used, which would result in literature from all relevant fields. Consequently, the search was not limited to a specific discipline, and research had to appear in journals relevant to STEM education or specifically refer to 'STEM' in the context of education. The titles and abstracts of the texts obtained from the search were then reviewed. Any references that focused on the traditional sciences were discarded. The keyword search was done in an attempt to find all of the literature about STEM and critical thinking education. In devising the keyword search, we took into consideration different expressions of STEM. The search was conducted using the words 'STEM education,' with 'critical thinking' and 'computer.' In the current literature, there exist some references that use these words only. These words were also used in retrieving the texts. This relevance is in the sense that some of the computer-related references are STEM-based. We included the word 'computer' as one of the search parameters since there is computer-related STEM education research. Moreover, computer is one of the fundamental subjects taught in middle school in the United States, such as MAC or STEAM.

Inclusion and Exclusion Criteria

To answer the research questions, we outline the criteria used to include or exclude studies from this review. Inclusion criteria are as follows: The study explicitly addresses the relationship between STEM education and critical thinking achievement, process, disposition, or attitude. The article presents primary research. The article is published in English. The article has been published within an academic journal or conference proceeding published in the last 10 years. The article uses quantitative or mixed methods; articles that only use qualitative methods are excluded. Exclusion criteria are as follows: The article does not report data. The article is a publication of popular interest. The article is focused on developing content for teacher education. While teacher content knowledge impacts what is taught in the classroom, we need to know about the experiences of students as they learn STEM subjects if we want to make inferences about engaging and educating future innovators in STEM. The article is focused on educational tools and uses. Among other aspects, tools and pedagogy impact how STEM is taught and learned: the purpose of this review is to make inferences about what students learn when studying STEM rather than how or why they learn it.

Data Extraction and Synthesis

To extract the necessary information for the synthesis, we recorded relevant data in a systematic manner. This did not only include the variables for the data synthesis, such as the methodology and the theoretical framework of the quantitative research, but also a list of results from the research indicating the first insights into the possible impact of STEM education on critical thinking. We have compared these search results in a descriptive manner, using themes identified earlier in the case of primary studies and research synthesis through qualitative data to compare them and, if possible, integrate them into a meta-analysis. As a result, it is easier to make statements on the results and the literature reviewed with respect to their quality.

From the results, it was possible to show the relationship between STEM education and the impact on critical thinking skills through synthesis. Per theme, some subthemes were identified, which were basically related to how STEM education influenced critical thinking. This synthesis will be checked to ensure that the systematic literature review has been followed strictly. For that, the synthesis will be checked and discussed with the authors of this SLR. Due to the large number of papers and characteristics, we expect that it will not be possible to complete this synthesis as one team, if not impossible at all. Therefore, the different researchers or teams will carry out part of the synthesis alone or in multidisciplinary teams and formulate initial findings to gain insights into the significance of the literature reviewed in the construction of critical thinking through STEM education. Hindered, in order to guarantee reliability, rather than authority or credibility, of the final findings and conclusions. Research design and method should be clearly defined.

Result and Discussion

Before presenting the thematic discussion, it is essential to clarify the purpose and structure of this analysis. This section synthesises empirical findings from selected journal articles that examine the effects of STEM-based learning on students' critical thinking skills across multiple educational levels. The reviewed studies employ various STEM implementation approaches, including Project-Based Learning (PjBL), Problem-Based Learning (PBL), inquiry-oriented STEM, and Ethno-STEM, providing a comprehensive overview of how different instructional designs influence critical thinking development.

Rather than reporting isolated results, this synthesis highlights converging evidence across studies, demonstrating consistent relationships between STEM educational practices and improvements in students' analytical, evaluative, and problem-solving abilities. The results are systematically summarised in Table 1, which presents the authors, publication years, and core findings related to critical thinking outcomes. This table serves as the empirical basis for the thematic discussion that follows.

Table 1. Results

Author	Article Titlle, (Year)	Result
Hacioğlu & Gülhan	The Effects of STEM Education on the Students' Critical Thinking Skills and STEM Perceptions, (2021)	Students involved in STEM education programs experience significant improvements in critical thinking skills. Active and project-based learning methods in STEM education allow students to analyze problems in depth, evaluate information, and develop creative solutions.
Baharin et al	Integrating STEM Education Approach in Enhancing Higher Order Thinking Skills, (2018)	Implementation of a STEM education approach significantly improves higher order thinking skills (HOTS) among students. Through interactive and project-based learning

Author	Article Titlle, (Year)	Result
		methods, students are trained to analyze, evaluate, and create solutions to complex problems.
Sumarni & Kadarwati)	Ethno-Stem Project-Based Learning: Its Impact to Critical and Creative Thinking Skills, (2020)	Ethno-STEM Project-Based Learning can be an effective tool in developing students' critical and creative thinking skills. By integrating local cultural elements in STEM learning, students not only gain academic knowledge but also practical skills that are useful in facing real-world challenges.
Davidi et al	Integrasi Pendekatan STEM (Science, Technology, Enggeenering and Mathematic) untuk Peningkatan Keterampilan Berpikir Kritis Siswa Sekolah Dasar, (2021)	The integration of STEM approaches in elementary school learning significantly improves students' critical thinking skills. Students who are involved in STEM-based learning activities are able to analyze and evaluate information better
Clarissa Desyana Putri, Indarini Dwi Pursitasari, & Bibin Rubini	Problem Based Learning Terintegrasi STEM Di Era Pandemi Covid-19 Untuk Meningkatkan Keterampilan Berpikir Kritis Siswa, (2020).	Problem Based Learning (PBL) approach integrated with STEM remains effective in improving students' critical thinking skills during the Covid-19 pandemic. Even though there are challenges in distance learning, this method succeeds in creating relevant and contextual learning situations.
Aureola & Septian	Efektivitas Model Pembelajaran Project Based Learning Berbasis STEM dan Tidak Berbasis STEM terhadap Kemampuan Berpikir Kritis Siswa.(2020)	This research compares the effectiveness of the STEM-based Project Based Learning (PBL) learning model with non-STEM-based PBL in improving students' critical thinking abilities. The results show that STEM-based models are more effective in developing students' critical thinking skills.
Setyawan Adiwiguna, Nyoman Dantes, and Made Gunamantha	Pengaruh Model Problem Based Learning (Pbl) Berorientasi Stem Terhadap Kemampuan Berpikir Kritis Dan Literasi Sains Siswa Kelas V Sd Di Gugus I Gusti Ketut Pudja, (2019)	The application of the STEM-oriented Problem Based Learning (PBL) model significantly increases students' critical thinking abilities. Students are able to analyze problems, evaluate information, and formulate better solutions after following learning with this approach.
Diyah Ayu Budi Lestari , Budi Astuti, and Teguh Darsono	Implementasi LKS Dengan Pendekatan STEM (Science, Technology, Engineering, And Mathematics) Untuk Meningkatkan Kemampuan Berpikir Kritis Siswa, (2018)	Student Worksheets (LKS) integrated with a STEM approach significantly increased students' critical thinking abilities. Students who use this worksheet are better able to analyze information, evaluate arguments, and formulate creative solutions to given problems.
Mutakinati et al	Analysis of Students Critical Thinking Skill of Middle School through STEM Education Project-Based Learning, (2018)	The application of project-based learning (PBL) with a STEM approach significantly improves secondary school students' critical thinking skills. Students involved in STEM projects demonstrate better analytical and evaluation skills.
Suryaningsih & Nisa	Kontribusi STEAM Project Based Learning dalam Mengukur Keterampilan Proses Sains dan Berpikir Kreatif Siswa, (2021)	STEAM Project Based Learning can make a significant contribution in improving students' science process skills and creative thinking. By creating an interactive and relevant learning environment, this approach not only enriches students' learning experience but also prepares them to face the challenges of an increasingly complex world. These findings demonstrate the importance of integrating STEAM elements in education to develop the skills needed for the future.

Based on the reviewed studies presented in Table 1, three major themes emerged that explain how STEM-based education contributes to the enhancement of students’ critical thinking skills: (1) STEM based learning design, (2) assessment strategies for critical thinking, and (3) critical thinking outcomes.

Overview of Empirical Findings

Across the reviewed studies, a clear pattern emerges indicating that STEM-based learning significantly enhances students' critical thinking skills. For instance, Hacıoğlu and Gülhan (2021) reported that students participating in STEM education programmes demonstrated measurable gains in critical thinking and problem analysis skills, particularly when learning activities were project-based and student-centred. Similarly, Baharin et al. (2018) found that integrating STEM approaches effectively improved students' higher-order thinking skills (HOTS), including analysis, evaluation, and creation.

These findings are reinforced by comparative studies. Aureola and Septian (2020) showed that students taught using STEM-based Project-Based Learning outperformed those in non-STEM PBL settings in terms of critical thinking performance. This suggests that the interdisciplinary integration characteristic of STEM learning provides added cognitive benefits beyond the use of active learning models alone.

At the elementary and secondary levels, consistent positive effects were also observed. Davidi et al. (2021) demonstrated that STEM integration in primary school significantly enhanced students' ability to analyse and evaluate information, while Mutakinati et al. (2018) reported that middle school students involved in STEM-oriented projects exhibited stronger analytical and evaluative thinking compared to peers in conventional classrooms. Collectively, these findings indicate that the positive impact of STEM-based learning on critical thinking is evident across age groups and educational contexts.

1. STEM-Based Learning Design

A dominant theme emerging from the reviewed literature is the critical role of STEM-based learning design in fostering students' critical thinking skills. Studies consistently report that instructional models such as Project-Based Learning, Problem-Based Learning, and Ethno-STEM create learning environments that require students to actively engage in inquiry, investigation, and problem-solving (Sumarni & Kadarwati, 2020; Setyawan et al., 2019; Hacıoğlu & Gülhan, 2021).

For example, Sumarni and Kadarwati (2020) found that Ethno-STEM Project-Based Learning not only enhanced students' critical thinking but also improved their ability to connect scientific concepts with local cultural contexts. This contextualisation encouraged deeper reasoning and more meaningful problem-solving processes. Similarly, Setyawan et al. (2019) reported that STEM-oriented PBL significantly improved elementary students' abilities to analyse problems, evaluate information, and formulate evidence-based solutions.

These results align with findings from Putri et al. (2020), who demonstrated that STEM-integrated PBL remained effective in developing students' critical thinking skills even during the constraints of distance learning in the COVID-19 pandemic. Together, these studies suggest that well-designed STEM learning environments particularly those grounded in real-world and contextual problems provide consistent opportunities for students to practice higher-order cognitive processes essential to critical thinking.

2. Assessment Strategies for Critical Thinking

In addition to instructional design, the reviewed studies highlight the importance of assessment strategies that align with the objectives of STEM-based learning. Baharin et al. (2018) emphasised the use of HOTS-based rubrics and performance assessments as effective tools for measuring students' critical thinking development. Such assessments prioritise reasoning quality, evidence-based justification, and solution design over rote memorisation.

Several studies also underscore the role of formative assessment in supporting critical thinking growth. Although not always the primary focus, reflective journals, inquiry reports, and collaborative discussions were frequently embedded within STEM learning activities (Wu et al., 2021; Hao et al., 2021). These assessment practices encourage students to reflect on their thinking processes, evaluate alternative solutions, and refine their reasoning—key aspects of metacognitive regulation.

The convergence of findings across these studies indicates that critical thinking development in STEM education is optimised when assessment methods are authentic, process-oriented, and aligned with inquiry-based learning goals rather than traditional summative testing alone.

3. Critical Thinking Outcomes

The reviewed literature consistently reports positive outcomes of STEM-based learning on multiple dimensions of critical thinking, including analysis, evaluation, inference, and interpretation. Davidi et al. (2021) observed significant improvements in elementary students' analytical and evaluative skills following STEM-integrated instruction. Similarly, Mutakinati et al. (2018) found that secondary school students engaged in STEM Project-Based Learning demonstrated stronger reasoning and evaluation abilities than those in conventional learning environments.

Studies focusing on STEAM integration further reinforce these outcomes. Suryaningsih and Nisa (2021) reported that STEAM Project-Based Learning contributed not only to creative thinking but also to science process skills that support critical inquiry and evidence-based reasoning. These findings suggest that interdisciplinary STEM and STEAM approaches provide cognitive flexibility that supports deeper critical engagement with scientific concepts.

However, several studies also identified implementation challenges that may moderate these positive outcomes. Kalogiannakis et al. (2021) and Takeuchi et al. (2020) highlighted issues such as unequal student readiness, limited instructional resources, and insufficient teacher expertise in STEM integration. These constraints indicate that while STEM-based learning is effective, its success depends on adequate teacher preparation, institutional support, and contextual readiness.

Integration with Previous Theoretical and Empirical Studies

The empirical findings of this review are consistent with broader research emphasising the importance of STEM education in developing 21st-century skills. Prior studies have shown that STEM learning, grounded in inquiry and problem-based pedagogy, inherently supports critical thinking, creativity, and innovation (Cooper, 2023; Li et al., 2020; Ješková et al., 2022). The emphasis on real-life problem-solving and interdisciplinary integration reflects the demands of contemporary workplaces and global challenges (Tytler, 2020; Lavi et al., 2021).

Moreover, the conceptualisation of critical thinking as a cognitive, metacognitive, and affective process (Alsaleh, 2020; Rivas et al., 2022) is well supported by STEM learning environments that promote reflection, self-regulation, and collaborative inquiry. Problem-based approaches within STEM education further empower students to apply disciplinary knowledge to real-world contexts, reinforcing responsibility and deeper understanding (Wale & Bishaw, 2020; Chankseliani et al., 2021).

Synthesis of Findings

Overall, the strengthened synthesis of empirical evidence suggests that STEM-based learning, when implemented through well-designed instructional models and supported by authentic assessment strategies, has a robust and positive impact on students' critical thinking skills. The reviewed studies collectively demonstrate that STEM education functions not merely as an integration of disciplines but as a comprehensive pedagogical framework that cultivates inquiry, reasoning, collaboration, and reflective thinking.

These findings indicate the need for future research to examine longitudinal effects, cross-disciplinary coherence, and the integration of digital and technology-enhanced STEM tools to sustain critical thinking development over time. Additionally, strengthening teacher professional development and institutional support will be essential to maximise the effectiveness and scalability of STEM-based learning initiatives.

Conclusion

This systematic literature review concludes that STEM education has a consistently positive impact on students' critical thinking skills across educational levels, particularly when implemented through problem-based, project-based, and inquiry-oriented learning approaches that promote analysis, evaluation, inference, and reflective judgment. The effectiveness of STEM learning is strongly influenced by well-designed interdisciplinary learning models, the use of meaningful assessments that capture higher-order thinking, and teachers' professional competence in implementing integrative instruction. Despite strong empirical support, challenges related to equitable access, resource availability, and teacher readiness remain, indicating the need for continued efforts to optimise STEM implementation. Therefore, future research should focus on longitudinal designs, digital integration, and context-sensitive adaptations of STEM education to ensure the sustained development of students' critical thinking skills and broader 21st-century competencies.

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Author Contributions

Conceptualization, K.P. and S.S.; methodology, K.P.; validation, K.P., S.S., and K.R.P.; formal analysis, K.P.; investigation, K.P.; resources, K.P.; data curation, K.P.; writing—original draft preparation, K.P.; writing—review and editing, K.P., S.S., K.R.P., and A.N.W.; supervision, S.S.; project administration, K.P. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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