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Bridging Minds: Systematic Literature Review of STEM Approaches in Cultivating Critical Thinking in Science Education

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Abstract: This study systematically reviews STEM-based learning models and media designed to enhance students' critical thinking skills. A total of 27 Scopus-indexed articles published between 2020 and 2024 were analyzed using a systematic literature review (SLR) approach. The analysis focused on publication trends, thematic emphases, key findings, and implementation challenges. Results indicate that STEM integration through models such as Problem-Based Learning (PBL) and Inquiry-based learning supports the development of several critical thinking indicators, especially explanation, inference, and decision-making. Quantitative findings from some studies show that improvements are often moderate, with the indicator of advance clarification consistently emerging as the weakest. Media such as worksheets and e-modules are found to facilitate structured inquiry and independent learning, yet their effectiveness remains constrained by limited teacher readiness, short implementation cycles, and challenges in interdisciplinary integration. STEM-based learning contributes positively to critical thinking development, though its impact varies across indicators and contexts. Future studies are recommended to design and evaluate targeted learning models, such as the Clarity Learning Model (CLM), which focuses on strengthening advance clarification while supporting other critical thinking dimensions.

Keywords: Critical thinking; Design-based learning; Learning models; Science education; STEM

Introduction

The goal of STEM (science, technology, engineering, and mathematics) education is to give students the information and abilities they need to deal with changes in a technologically advanced world. STEM programs that integrate science and engineering concepts and are oriented towards solving real-world problems have been shown to significantly improve science learning and knowledge retention among students compared to traditional methods (Anwar et al., 2023; Permanasari et al., 2021; Gusman et al., 2023). Early and continuous STEM enrichment, especially for underrepresented and underserved students, has been shown to improve achievement, placement in advanced courses, and college matriculation rates, thereby helping to close the educational opportunity gap (Olszewski-Kubilius, 2023; Galvez et al., 2024; Yanti et al., 2025). The integration of practical inquiry and real-world challenges in STEM learning encourages students to connect abstract concepts with everyday life, which in turn enhances deep understanding and higher-order thinking (Tan et al., 2023; Huang et al., 2022; Monika et al., 2023). In addition, teacher involvement and mentoring programs play a role in closing achievement gaps, increasing interest in STEM, and fostering student

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ownership in the field (Olszewski-Kubilius, 2023; Weng et al., 2022; Wintribrata et al., 2025).

Critical thinking is one of the 21st-century skills that STEM education can best foster in students. With this ability, kids can assess arguments, create solutions, examine data, and make wise decisions (Raj et al., 2022; Shanta & Wells, 2022; Rizki et al., 2021). Critical thinking also supports students in understanding complex concepts, constructing logical arguments, and achieving better academic performance (Jariyah & Husamah, 2024; Khairati et al., 2021). In addition, students with these skills are better prepared to face a rapidly changing world because they are able to distinguish credible information, learn independently, and adapt flexibly (Anggraeni et al., 2023; Susongko et al., 2024; Pratiwi & Doyan, 2024; Putri et al., 2023). This is especially pertinent to STEM and the real world, because applying information necessitates both creativity and reasoning (Sari et al., 2021; Kurniahtunnisa et al., 2023).

Several studies show that STEM approaches, particularly those based on projects, integration, and problem solving, consistently improve students' critical thinking skills. The strongest effects were found at the high school level (Yreck, 2024; Sahabudin et al., 2024; Zan et al., 2023). It has been demonstrated that students who are taught utilizing the STEM approach perform exceptionally well on critical thinking tests across a range of age groups and mathematics and scientific situations (Shanta & Wells, 2022; Widyawati et al., 2024). Furthermore, authentic experiences in engineering design and STEM projects encourage students to select relevant knowledge, reason logically, and find solutions to real-world problems (Nehru et al., 2024; Anwar et al., 2023). Therefore, STEM not only broadens knowledge but also equips pupils with the critical thinking ability they need to handle the challenges of the twenty-first century (Nilyani et al., 2023).

However, implementing STEM in science education is not easy, and there are still challenges in ensuring its integration is truly effective in developing critical thinking skills. Numerous research have looked at the connection between STEM and critical thinking, for example in the context of physics (Sulisworo & Kaliappen, 2021), mathematics (Nurhikmayati et al., 2024), and analytical skills in general (Hidayat et al., 2024). However, these reviews tend to focus on specific subjects or skills and do not provide a comprehensive overview of STEM research trends in improving critical thinking in science education at large. Therefore, this study conducts a systematic literature review (SLR) to identify, map, and analyze research trends on STEM integration in developing critical thinking ability in science learning. This study is crucial because it can give a comprehensive picture of the direction of previous research, highlight unexplored areas, and give researchers and educators a better foundation for creating future advances in STEM-based science education.

Method

This study synthesized previous research on the integration of STEM in improving critical thinking abilities using a Systematic Literature Review (SLR) approach (Abelha et al., 2020). Because it enables researchers to thoroughly map, assess, and spot trends in published studies, SLR was selected (Nandiyanto et al., 2023). To guarantee openness, rigor, and reproducibility, the review procedure adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) criteria.

Eligibility criteria were established to narrow the scope of the review. Publications were limited to the years 2020–2024 to ensure recency and relevance. Due to their established quality and reliability, only peer-reviewed journal articles that were indexed in SCOPUS were included. Articles had to be written in English to ensure wider accessibility and global relevance. In terms of focus, only studies addressing the integration of STEM or STEAM in relation to critical thinking skills in science education were considered.

The SCOPUS database, which was selected for its extensive coverage of respectable worldwide publications, was used to collect data on May 25, 2025. The search strategy employed Boolean operators as follows: "STEM" OR "STEAM" AND "Critical thinking skills" OR "Critical thinking ability". This formulation avoided redundancy and ensured that only articles directly addressing the relevant topics were retrieved. The inclusion of the STEAM keyword was intentional, since several studies explicitly adopt the STEAM approach instead of STEM, thereby enriching the scope of analysis.

Duplicate records were eliminated first in the screening procedure, and then the titles and abstracts were reviewed to determine their relevancy. Excluded from consideration were articles that did not discuss critical thinking abilities in relation to STEM or STEAM education. Full-text assessment was then conducted to confirm alignment with the research objectives. From the entire pool of retrieved studies, 27 articles were deemed relevant and included in the final analysis.

Data analysis was conducted through a systematic literature review, extracting essential information from each article, including research objectives, learning approaches applied, key findings, and the contribution of STEM to critical thinking skills. This analytic process enabled the identification of patterns, differences, and research directions without employing bibliometric analysis.

The entire procedure—from identification, screening, eligibility, to inclusion is illustrated in a PRISMA flow diagram (Figure 1), providing a clear visual representation of the systematic steps undertaken in this study.

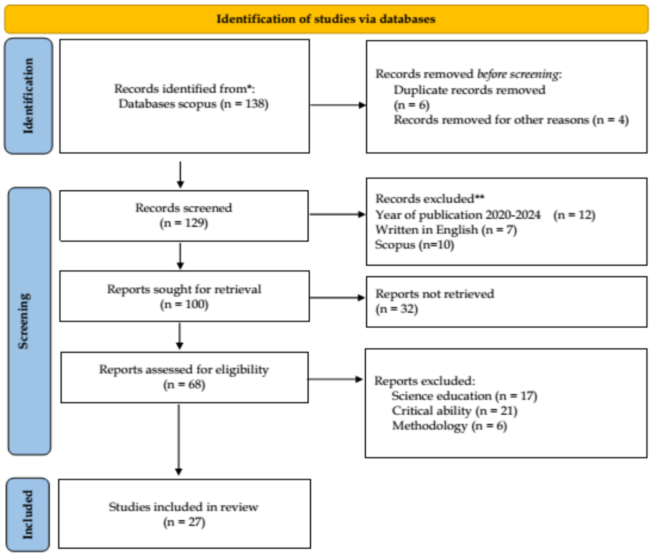

Figure 1. The process of article selection

Result and Discussion

Yearly Trend of Publication Number

Currently, there are 27 studies in our review published between 2020 and 2024 in international journals indexed by Scopus. Figure 2 depicts the evolution of STEM-related publications for enhancing critical thinking skills in science education. Figure 2 depicts the annual publishing pattern from 2020 to 2024, illustrating the growth and variations in research findings. The largest number of publications during the period occurred in 2021 and 2024, with seven documents each, indicating notable peaks of research activity or interest in those years. In contrast, the number of publications declined after 2021, reaching its lowest point in 2023 with only three documents. This was followed by a recovery in 2024. Despite these fluctuations, the overall trend reflects sustained scholarly engagement, with variations likely influenced by shifts in research focus. Furthermore, study on critical thinking is vital because it helps understand how humans analyse facts objectively, evaluate evidence rationally, and make logical and informed decisions (Musametov, 2021; Raj et al., 2022). This critical thinking ability is crucial in addressing complex issues, such as environmental concerns or 21st-century challenges, as it enables individuals to identify, assess, and select the best solutions based on in-depth analysis (Anggraeni et al., 2023). Research on critical thinking ability is widely conducted in the context of education, particularly to develop problem-solving, argumentation, and evidence-based decision-making skills (Verma et al., 2022; Sharma et al., 2022). In education, a critical thinking-based approach not only helps students build strong arguments and make sound decisions but also enhances self-awareness of cognitive biases and strengthens reflective abilities (Lamont, 2020; Simonovic et al., 2023). As a result, continued research into methods and tactics that promote critical thinking growth is vital, particularly in training individuals to adapt and make effective decisions in the face of more complex and dynamic global situations.

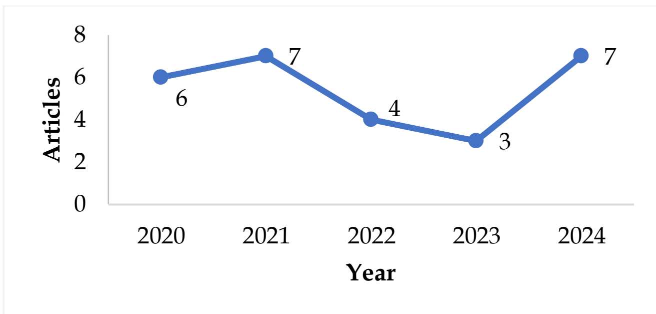

Figure 2. Annual scientific productions

STEM-Integrated Learning Model

Learning models that are widely integrated with STEM include STEM-integrated learning, Project-Based Learning, Inquiry Learning, Problem-Based Learning, and other models presented in Table 1.

Table 1. Leaning Model/Media Integrated with STEM

Author	Learning Model/Media Integrated with STEM
Mater et al. (2022), Yaki (2022), Rahmawati (2021), Sarwi (2024), AlZahrani (2024), and Zuhaida (2022)	Integrated STEM
Oyewo (2022), Nehru et al. (2024), Rohman (2024), and Ananda et al. (2023)	Project Based Learning
Zakiyah (2021), Prayogi (2024), and Isdĩanti̇ et al. (2021)	Inquiry
Pertiwi et al. (2024), Lubna (2023), and Parno (2021)	Problem Based Learning
Purwaningsih (2020)	Instruction Model
Sari (2020)	Contextual Problem
Ardianti et al. (2020)	Blended Learning
Handayani (2021), Purnamasari (2020), Kurniati (2021), Nurramadhani (2021)	e-Module
Sutarto (2021), Hartini (2020), and Widyawati et al. (2024)	Worksheets Integrated

Integrated-STEM

Based on the 27 articles analyzed, there were six studies that used an integrated STEM approach in the learning process. The review findings indicate that STEM integration is consistently employed as the primary approach to fostering students' critical thinking ability through contextual, exploratory, and interdisciplinary learning activities (Mater et al., 2022; Yaki, 2022; Rahmawati, 2021; Sarwi, 2024; AlZahrani, 2024; Zuhaida, 2022). The study by Mater et al. (2022) report provides aThrough group projects, study provides insightful information about how well STEM can enhance inference, interpretation, deduction, and evaluation skills. The strength of this study lies in the use of the valid and comprehensive California Critical Thinking Skills Test (CCTST) quantitative instrument. Similarly, Yaki (2022) shows that the STEM approach significantly improves five critical thinking indicators based on the Watson–Glaser framework, particularly through problem-based and collaborative activities.

Meanwhile, Rahmawati (2021) menambahkan elemen art dalam pendekatan STEAM added an art element to the STEAM approach and applied it to a "steamship" project on thermochemistry. Although this project encouraged active student engagement, the results showed that low initial conceptual understanding was the main obstacle in developing critical thinking indicators such as "Identify the Question at Issue." Sarwi's (2024) study presents an innovation through the STEM-R model, which integrates religious values into science education. The results show that this approach not only promotes critical thinking ability but also reflective thinking, particularly in the context of tahfidz schools that emphasize spirituality and ethical decision-making.

Similar findings were also reported by AlZahrani (2024), who showed that STEM-based science and mathematics learning units have a significant effect on improving critical thinking ability ($\eta^2 = 0.80$). Through scientific investigations, laboratory experiments, and engineering design projects, students engage in activities that train them to formulate hypotheses, conduct tests, and draw logical conclusions in realistic contexts. Finally, Zuhaida (2022) emphasize a systematic process in planning and implementing STEM learning on the topic of "simple machines," which includes analyzing basic competencies, formulating indicators, and implementing learning to map critical thinking ability based on FRISCO indicators.

These six articles generally demonstrate that three key mechanisms are crucial to the STEM approach's ability to successfully enhance students' critical thinking skills: (i) the contextual integration of project activities with science and math curriculum (Mater et al., 2022; Yaki, 2022; AlZahrani, 2024); (ii) emphasis on inquiry processes, problem solving, and experiments based on questions formulated by students themselves (Zuhaida, 2022; AlZahrani, 2024); and (iii) the role of teachers in guiding scientific exploration and facilitating connections between values, science, and practice (Rahmawati, 2021; Sarwi, 2024).

Project Based Learning-STEM

Based on the 27 articles analyzed, five studies used a project-based learning model integrated with STEM. The review findings indicate that analyzed showed that the STEM-based Project-Based Learning (PjBL-STEM) approach was consistently used as the main strategy for fostering students' critical thinking ability at various levels and in various educational contexts. Although the topics and teaching materials varied, the common thread across all articles was that project-based learning contextualized through STEM principles can create a deep learning environment (Oyewo, 2022), a collaborative learning environment (Nehru et al., 2024). In all studies, PjBL-STEM not only serves as a pedagogical approach but also to train students to address real-world problems, develop solution strategies, and reflectively evaluate their project outcomes. The learning syntax becomes a proven framework for activating various aspects of critical thinking ability (Eja, 2020; Rohman, 2024). According to other studies, PjBL-STEAM helps children express their creativity through the visual arts and can increase their motivation to learn science (Ananda et al., 2023).

The general findings from the five articles indicate that the implementation of PjBL-STEM is effective in improving students' critical thinking ability with moderate to high improvement. Improvements in critical thinking ability are reflected in various indicators such as analysis, inference, and explanation. Nehru et al. (2024) noted a significant increase in Type 2 thinking (reflective and rational thinking), where students responded more slowly and with clear objectives based on aspects of critical thinking ability. Furthermore, Oyewo (2022) demonstrated students' ability to design natural coagulants through an interdisciplinary approach combining concepts from chemistry, engineering, and the environment. It is also proven that PjBL-STEM can enhance critical thinking ability, achieving an N-Gain of 0.5–0.6 (moderate category) (Rohman, 2024; Nehru et al., 2024). Oyewo (2022) and Eja (2020) achieved high-category results through authentic projects and peer assessment. Additionally, there are critical thinking indicators that are still weak, particularly in the areas of reasoning and argument analysis, due to students' lack of practice in developing logical reasoning and their ability to evaluate and distinguish between strong and weak arguments (Nehru et al., 2024).

The main mechanisms underlying the success of PjBL-STEM in enhancing critical thinking can be identified through: (i) investigative and exploratory processes that require students to think systematically (Rohman, 2024), (ii) integration of science, technology, engineering, and mathematics content in authentic contexts (Nehru et al., 2024) (iii) reflection and evaluation in the final stage of the project (Rohman, 2024), (iv) the use of authentic assessments such as rubrics, portfolios, and peer assessment, which encourage individual and collaborative accountability (Eja, 2020). Overall, PjBL-STEM not only encourages students to complete projects, but also to construct arguments, evaluate alternative solutions, and make decisions based on data and theory. The foundation of critical thinking is this.

Inquiry-STEM

Based on the 27 articles analyzed, there were three studies that used an inquiry learning model integrated with the STEM approach. The integration of inquiry-based learning and STEM showed high effectiveness in encouraging the development of critical thinking skills, both at the high school student level and among prospective teachers. The three studies Zakiyah (2021), Prayogi (2024), and Isdïantï et al. (2021), consistently emphasize that structured investigative and exploratory processes form the primary foundation for building higher-order thinking skills.

Zakiyah's study (2021) demonstrates how implementing STEM-based learning with an inquiry method can help students enhance their critical thinking skills and conceptual understanding. Through exploration activities, hypothesis testing, and collaborative discussions, students are actively engaged in a learning process that requires analytical thinking. However, this study does not explicitly detail critical thinking indicators and does not evaluate the sustainability of the intervention's effects. Meanwhile, Prayogi (2024) not only tests the effectiveness of inquiry but also develops an inquiry-creative model that combines the scientific process with elements of creativity. This paradigm was found to be much more effective in improving four critical thinking indicators: analysis, inference, evaluation, and decision making. The addition of creativity elements encourages students not only to find a single solution but also to create various innovative alternative solutions and reflect on the effectiveness of these solutions in real-world contexts. The study by Isdïantï et al. (2021) adds a strong empirical dimension through a quasi-experimental approach in the context of secondary school science education. The inquiry-based STEM learning package developed successfully improved students' critical thinking ability significantly across five key indicators: Basic Clarification, Decision, Inference, Advanced Clarification, and Supposition and Integration. High N-Gain values, along with students' highly positive responses to project-based learning and technology observation, indicate that this approach is effective and favored by students. Learning is linked to real-world contexts (exploring excavators as simple machines), making students' thinking processes more reflective and applicable.

The main mechanisms underlying the success of inquiry-based STEM learning in improving critical thinking can be identified through: (i) a systematic process of scientific exploration and investigation—students observe, construct hypotheses, test ideas through experiments, and relate them to data (Zakiyah, 2021; Isdïantï et al., 2021), (ii) integration of science, technology, engineering, and mathematics content into contextual scenarios and challenges engages the evaluation and problem-solving sides (Prayogi, 2024), (iii) reflection and scientific decision-making, including the ability to develop various alternative solutions and evaluate their effectiveness (Prayogi, 2024; Isdïantï et al., 2021) and (iv) strengthening the creative dimension in scientific inquiry, such as designing innovative experiments or problem-based products, which contribute to the development of scientific reasoning (Prayogi, 2024).

Problem Based Learning-STEM

Based on three studies analyzed, Pertiwi et al. (2024), Lubna (2023), and Parno (2021) it can be concluded that the STEM-based Problem-Based Learning (PBL-STEM) approach consistently demonstrates effectiveness in improving students' critical thinking ability, even when applied in diverse contexts, levels, and learning media. The study by Pertiwi et al. (2024) developed a website-based e-module that integrates the STEM approach with the Problem-Based Contextual Learning (PBCL) model, utilizing PhET Virtual Lab for thermochemistry topics. The results showed a significant improvement in interpretation, analysis, evaluation, and inference skills, with an N-Gain of 0.69 (high category). Learning based on real phenomena, supported by interactive simulations, encourages kids to think systematically while formulating problems, developing hypotheses, and evaluating data reflectively.

Similarly, Lubna (2023), who studied science education students in online learning, and Parno (2021), who tested high school students face-to-face with the help of Virtual Simulation Media (VSM), both noted a significant increase in Critical Thinking Abilities (CTA). The high N-Gain values (0.74–0.75) in both studies indicate that the integration of PBL and STEM promotes meaningful and cognitively challenging learning. Parno

(2021) noted that the use of VSM successfully bridged the abstraction of optical material, enabling all CTA indicators to develop, while Lubna (2023) emphasized the importance of reflection and contextualization of problems in promoting inference and evaluation indicators.

Although the results were positive, the three studies also identified implementation challenges. Parno (2021) highlighted low initial motivation and misconceptions among students due to the abstract nature of physics topics. Lubna (2023) revealed limitations in the authenticity of problems and depth of reflection in the early stages of online learning. Meanwhile, Pertiwi et al. (2024) found that many students struggled to understand thermochemical concepts without adequate visualization, and teachers were not yet accustomed to using interactive digital media. These challenges emphasize that the effectiveness of PBL-STEM is greatly influenced by structured learning design, appropriate media selection, and facilitator competence in guiding problem-based scientific exploration. Overall, the mechanisms of PBL-STEM's success in improving critical thinking ability can be traced through three main aspects: (i) active student involvement in solving complex authentic problems, (ii) integration of STEM content with contextual and reflective learning approaches, and (iii) utilization of technology and visual media that support the representation of abstract concepts. With this strategy, students receive instruction on how to formulate logical arguments in addition to problem-solving techniques, evaluate alternative solutions, and make evidence-based decisions—core elements of critical thinking.

Other STEM-Integrated Learning Models

A systematic literature review of three studies combining the STEM approach with specific learning strategies such as modeling instruction (Purwaningsih, 2020), contextual problem (Sari, 2020) and blended learning (Ardianti et al., 2020) shows a significant contribution to improving students' critical thinking skills. Despite using different instructional materials and learning scenarios, all studies consistently found that STEM-based instructional design can develop various aspects of critical thinking, including inference, explanation, strategy and tactics, and self-regulation.

The study by Purwaningsih (2020) presents the integration of STEM with modeling instruction in work and energy learning. Using MI syntax combined with PhET experiments and skateboard track construction projects, students are trained to develop skills ranging from elementary clarification to strategies and tactics. Meanwhile, Sari (2020) applied the STEM-CP approach through the development of optics teaching materials based on contextual problems. This intervention showed significant improvements in interpretation, inference, explanation, and evaluation, especially after students were exposed to real-life problems closely related to their daily lives. On the other hand, Ardianti et al. (2020) demonstrated that a STEM approach based on blended learning can be an effective alternative in a blended learning context (online-offline). Through the integration of hands-on experiments and online collaborative activities on Edmodo, students showed improvements in five critical thinking indicators measured, with an average N-Gain in the moderate-high category. This strategy successfully combines the flexibility of technology and hands-on experience in supporting higher-order thinking processes.

However, the three studies also noted several implementation challenges, including students' limited mastery of initial concepts, procedural thinking habits, and teachers' lack of familiarity with developing integrated and contextual STEM learning syntax. Other challenges include limitations in digital infrastructure (Ardianti et al., 2020) the absence of control groups (Purwaningsih, 2020; Sari, 2020) and the lack of long-term evaluation. Therefore, the effectiveness of the STEM approach based on instructional strategies is highly dependent on the quality of instructional design, teacher readiness, supporting media, and authentic assessment that reflects students' critical thinking ability comprehensively. Overall, the three studies reinforce STEM's position as a flexible and adaptive approach that can be integrated with various learning models to develop a critical thinking ability in a contextual, reflective, and applied manner.

Media Integrated through STEM Approach

E-Modules Integrated with STEM Approach

Based on the 27 articles analyzed, four studies used e-modules integrated with STEM. All articles emphasized that the use of e-modules enabled the application of independent, flexible learning principles oriented toward the development of high-order thinking skills. Research by Handayani (2021) and Purnamasari (2020) showed that e-modules designed with STEM-PBL syntax can activate students' thinking processes in formulating problems, proposing hypotheses, conducting experiments, and drawing conclusions. Meanwhile, Kurniati (2021) integrated social media into e-modules to enhance interactivity and accessibility during online learning, and Nurramadhani (2021) explored the quality of students' questions as an initial indicator of critical thinking triggered by activities in STEM-based e-modules. Although not all articles have tested the effectiveness of the product through full experiments, preliminary results show a positive trend. Kurniati (2021) further reported that teachers and students supported the need for integrated PBL-STEM e-modules, but their use remains very limited (only 12.5% of teachers). These findings confirm that STEM-based e-modules can stimulate reflective inquiry, problem-solving, and argumentation processes, yet their effectiveness depends heavily on the quality of design, scaffolding, and alignment with students' experiences. The low uptake further emphasizes how important teacher preparedness is to the success of integrating STEM through e-modules.

Worksheets Integrated with STEM Approach

According to a survey of three articles, one of the most flexible and successful educational approaches for fostering students' critical thinking abilities, especially in science education, is designing worksheets based on the STEM method (Sutarto, 2021; Hartini, 2020; Widyawati et al., 2024). The worksheets created in the three studies serve not only as practice aids, but also for conceptual inquiry, contextual experimentation, and the development of higher-order thinking skills. The most developed aspects are generally explanation (explaining phenomena, answering data-based questions), reporting experiment results (training accuracy, observation, and data reporting), and deciding actions (making decisions based on experimental evidence). Conversely, indicators such as self-regulation (Sutarto, 2021) and formulating questions (Hartini, 2020) tend to be low, indicating that students' reflective and independent inquiry skills still require further development. This shows that while worksheets provide flexibility and contextual relevance, their ability to foster deeper reflective thinking is still limited. Such weaknesses can also be linked to barriers in classroom implementation, particularly constraints of time and teacher preparedness.

Barriers to STEM Implementation

Although various studies show that the STEM approach contributes positively to improving critical thinking ability, several significant implementation barriers have also been identified in different learning contexts. One of the main challenges is the lack of readiness among teachers or lecturers to design relevant and interdisciplinary projects. Teachers have difficulty developing STEM programs that truly combine science, technology, engineering, and mathematics aspects holistically into a coherent sequence of activities (Rahmawati, 2021). his is due to the lack of practical training that equips teachers with project-based integrative learning design skills. In addition, managing learning time is also a recurring obstacle. In practice, STEM learning models, especially those based on projects (PjBL) or problems (PBL), require more time to complete a learning cycle. Teachers often find it difficult to adjust the project syntax to the limited time allocation in class, so implementation tends to be incomplete or rushed (Parno, 2021). As a result, students do not have sufficient opportunity for in-depth reflection, even though reflection is a key element in the development of critical thinking skills. Another commonly found obstacle is the low level of active student participation, especially in stages that require reflective and exploratory thinking. Students are not yet accustomed to developing open-ended questions, analyzing data, or constructing logical arguments (Eja, 2020). This is due to learning habits that still tend to be oriented toward memorization and direct instruction. The lack of conceptual and pedagogical readiness among teachers is also a significant obstacle to the implementation of STEM. Most teachers lack experience or a deep understanding of the philosophy and principles of STEM and are unable to integrate exploratory activities into science learning. Many of them still adhere to teacher-centered expository learning patterns, where learning is dominated by lectures and conventional assignments, rather than inquiry-based or open exploration activities.

Overall, these barriers emphasize that the implementation of the STEM approach cannot be carried out instantly. Systemic support is required in the form of intensive training for teachers and lecturers, the provision of practical and flexible teaching tools, as well as educational policies that encourage interdisciplinary collaboration. In addition, the investigation showed that out of all the signs of critical thinking, the advance clarification indicator showed the lowest achievement, thus requiring greater attention and reinforcement in both instructional design and classroom practice. With such support, STEM learning can be implemented optimally to produce critical, creative, and adaptive learners capable of addressing the challenges of the 21st century.

Conclusion

This study confirms that the integration of STEM with active learning approaches supported by appropriate media contributes positively to the enhancement of students' critical thinking skills. Approaches such as PjBL, PBL, and Inquiry demonstrate potential in fostering contextual, collaborative, and higher-order thinking, although findings across studies are not entirely consistent and show variations in effectiveness. Learning media such as worksheets and e-modules support the implementation of active learning syntax; however, certain indicators particularly advance clarification remain relatively low and require greater attention. Despite these benefits, the implementation of STEM-based learning continues to face challenges, including time constraints, difficulties in cross-disciplinary integration, and teacher readiness.

Addressing these issues through targeted training, adaptive learning tools, and supportive educational policies will be crucial to maximizing its impact. Overall, integrative and contextual STEM learning shows strong potential in developing critical thinking skills. Future research could focus on the use of the Clarity Learning Model (CLM), specifically designed to strengthen the advanced clarification indicator, with the expectation that it may also contribute to improving other critical thinking indicators more evenly.

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Author Contributions
Conceptualization, methodology, B.N.I. and P.; validation, formal analysis, P. and B.N.I.; investigation, resources, B.N.I and M.A.; writing—original draft preparation, writing—review and editing, B.N.I.; visualization, supervision P. and M.A.; project administration, funding acquisition, P. and B.N.I.

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Conflicts of Interest
The authors declare no conflict of interest.

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