

THE IMPACT OF STEM-BASED LEARNING ON STUDENTS' CRITICAL THINKING SKILLS: A LITERATURE REVIEW

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ABSTRACT

Teachers play a crucial role in determining the success of STEM-based learning, particularly in implementing innovative teaching models and integrating science, technology, engineering, and mathematics into meaningful learning experiences. However, teacher-centered learning often limits students' opportunities to develop critical thinking (CT) skills. Therefore, STEM-based learning is considered an effective approach for fostering active participation, problem-solving skills, collaboration, and higher-order thinking skills. This study aimed to analyze the impact of STEM-based learning on students' CT skills and identify factors influencing the success of its implementation. The method used in this study was a Systematic Literature Review (SLR) following the PRISMA guidelines to ensure a systematic and transparent article selection process. Scientific articles were collected from the Google Scholar and Scopus databases using keywords related to STEM education and critical thinking skills. Of the 100 identified articles, 15 studies published between 2021 and 2026 met the inclusion criteria and were analyzed further. The findings revealed that all reviewed studies reported positive effects of STEM-based learning on students' CT skills. Improvements were consistently observed in students' abilities to analyze problems, evaluate information, make decisions, and develop problem-solving strategies through active and collaborative learning activities. Therefore, STEM-based learning can be considered an effective approach for enhancing students' critical thinking skills in science education.

Keywords: STEM; STEM based learning; critical thinking

INTRODUCTION

Science education is an interactive process between pupils and their learning environment aimed at building meaningful conceptual understanding (Susilowati, 2023). Science education not only emphasizes conceptual mastery but also plays a role in developing pupils' scientific attitudes (Purnawati & Yakin, 2025). The implementation of science education requires CT so that pupils can analyze problems, evaluate information, and make logical inferences (Halimah et al., 2023). For this reason, CT is a crucial aspect of education, as it enables pupils to address various real-world problems in a rational and evidence-based manner (Putri et al., 2025).

Critical thinking (CT) refers to the ability to examine, evaluate, and interpret information logically in order to make well-reasoned decisions (Rendi et al., 2024). CT is characterized by open-mindedness, curiosity, objectivity, and the ability to consider multiple perspectives before drawing conclusions (Ni'mah, 2022). In the studies reviewed, CT was operationalized through several key indicators, including interpretation, analysis, evaluation, inference, explanation, and self-regulation (Solihah et al., 2023). These indicators were selected because they are widely recognized in science education research as essential components of higher-order thinking skills and are highly relevant to STEM-based learning contexts. Among

these indicators, analysis, evaluation, and inference were the most frequently emphasized, as STEM learning requires students to analyze information, evaluate evidence and alternative solutions, and draw logical conclusions in solving real-world problems. The CT process generally involves several stages, including problem identification, information gathering and analysis, evaluation of possible solutions, and decision-making based on rational consideration and evidence-based arguments (Puling et al., 2024). In learning activities, these indicators are interconnected and form a continuous cognitive process that begins with understanding information, followed by analysis and evaluation, drawing conclusions, providing explanations, and finally engaging in self-reflection (Kalsum, 2025). This interconnection plays a very important role, particularly in science education, as it contributes to developing pupils' higher-order thinking skills to understand concepts and solve problems scientifically and systematically (Widodo & Safitri, 2025). However, previous studies still reveal several research gaps, particularly the limited variation of instruments used to measure critical thinking skills and the lack of in-depth analysis regarding the mechanisms through which STEM-based learning improves students' critical thinking abilities (Maric et al., 2023). Most studies primarily focus on general improvements in critical thinking scores without identifying which specific indicators, such as analysis, evaluation, or inference, are most significantly developed through STEM learning activities.

A STEM-based learning framework integrates scientific knowledge, technical knowledge, engineering knowledge, and mathematics within a holistic and

contextual learning experience (Muttaqiin, 2023). This approach emphasizes the solving of real-world problems relevant to daily life, enabling pupils to understand and applied the concepts they have learn in relevant real-world contexts (Ayuningsih et al., 2025). Additionally, STEM encourages pupils to actively engage through experiment- and project-based learning, enabling them to apply concepts in practice rather than merely understanding them theoretically (Rahmadhani, 2025). Therefore, implementing a STEM-based approach to learning enhances pupils' CTs, creativity, and the ability to solve problems.

STEM-based learning is closely linked to developing CTs, as this approach encourages pupils to actively participate in a scientific and structured solution-finding process (Huda et al., 2025). Through STEM learning, CTs can develop because pupils are confronted with real-world problems that require them Analysing info, evaluating various alternatives, deciding on rational and smart choices (Putra & Dewi, 2026). STEM activities such as experiments, design projects, and scientific investigations directly stimulate pupils' ability to analyze and evaluate data and results (Risnawati et al., 2025). This is where teachers play a really important part as facilitators in the learning process by designing challenging, contextual learning experiences that encourage pupils to think deeply, ensuring that learning is Don't just focus solely on the end result, but also on how you get there of developing CTs itself (Waluyo et al., 2025).

Although various studies shows STEM-based education's huge potential for improving CTs, A number of gaps still need further examination, as most studies emphasize general improvements without an in-depth exploration of students' critical

thinking processes (Sembiring, 2025). Furthermore, most research tends to focus on basic cognitive learning outcomes rather than higher-order thinking skills, such as analysis, evaluation, and complex problem-solving (Karina et al., 2025). This indicates a research gap, particularly in comprehensively examining how STEM-based learning can be designed and implemented effectively to optimize students' CTs within a more contextual and integrated learning context.

Therefore, a study using a SLR approach is needed to systematically identify, evaluate, and synthesize various relevant research findings. Through this approach, it is hoped that a more comprehensive picture of the effectiveness of STEM-based learning in enhancing CTs can be obtained.

Based on the above discussion, this study aims to analyze the effect of STEM-based learning on students' CTs in the classroom.

THEORETICAL FRAMEWORK

STEM

STEM stands for *Science, Technology, Engineering, and Mathematics*; it is an educational approach that integrates these four fields into a cohesive whole (Riawati et al., 2022). This approach does not view science as a separate field, but rather as interconnected and mutually supportive in understanding and solving real-world problems through active knowledge construction and problem-solving processes (Davidi et al., 2021). The relationship between STEM and critical thinking is grounded in constructivist learning theory and problem-based learning theory, which emphasize that students develop knowledge and higher-order thinking skills through active

engagement, investigation, collaboration, and authentic problem-solving experiences. STEM has emerged in response to the demands of the 21st century, which call for critical, creative, collaborative, and communicative skills (Lestari et al., 2025).

The STEM (*Science, Technology, Engineering, and Mathematics*) approach is a learning strategy is considered as an effective tool for improving students' CTs by introducing ideas relevant to the real world, so that students not only understand the material theoretically but also learn to apply it in various situations (Huda et al., 2025). In addition, STEM also helps develop 21st-century skills, such as critical thinking, creativity, collaboration, and communication (Rahayu et al., 2025).

Critical Thinking Skills (CTS)

CTs are a person's ability to analyze information in depth, evaluate various perspectives, and make logical, well-founded decisions (Puling et al., 2024). This skill involves not only understanding information, but also questioning, connecting, and evaluating the validity of an argument (Anisa et al., 2025).

CTs encompass several key components, such as the ability to analyze, evaluate, interpret, and draw conclusions (Mutmainnah et al., 2025). Analysis is the ability to break down information into smaller parts to make it easier to understand; evaluation assesses the validity and relevance of information; interpretation involves understanding the meaning of data; and drawing conclusions is based on logical evidence, these four elements are interrelated and form the foundation of CT (Rendi et al., 2024).

METHOD

This study employs a Systematic Literature Review (SLR) method aimed at

systematically and structurally identifying, evaluating, and synthesizing relevant research findings related to STEM-based learning and critical thinking skills. The SLR approach was chosen because it provides a comprehensive overview of research developments and integrates scattered empirical findings into a more comprehensive, evidence-based conclusion (Aulia & Maryati, 2026). The literature search was conducted in January–February 2026 using two primary databases, namely Google Scholar and Scopus. The search process used several keyword combinations, including “STEM education” AND “critical thinking,” “STEM-based learning” AND “critical thinking skills,” and “STEM approach” AND “higher-order thinking skills.” Only articles published in English and Indonesian between 2021 and 2026 were included in the review, while articles published in other languages were excluded. The inclusion criteria comprised: (1) empirical research articles related to STEM-based learning and critical thinking skills, (2) studies published in peer-reviewed journals, (3) studies involving primary, secondary, or higher education students, and (4) studies reporting measurable outcomes related to critical thinking skills. Meanwhile, the exclusion

criteria included: (1) review articles, conference papers, books, and theses, (2) studies not specifically discussing STEM learning and critical thinking, (3) articles without sufficient methodological information, and (4) studies with unclear or very limited sample characteristics. In the initial stage, researchers formulated research questions to guide the review process and determine the inclusion and exclusion criteria for article selection. The focus of this study is to examine the impact of STEM-based learning on CTs and to identify the factors influencing its effectiveness (Ayuningsih et al., 2025). The data collection process was conducted by searching scientific articles in Google Scholar and Scopus. These databases were selected based on considerations of publication quality and scope. Scopus is a reputable international database that provides indexed scientific articles meeting high-quality standards, thereby ensuring the credibility of the sources used. Meanwhile, Google Scholar was selected because it provides broader access to national and international literature relevant to the research topic. Therefore, the combination of these two databases was expected to produce more comprehensive and representative findings.

Table 1. Research Questions and Article Criteria

RQ 1	How does “STEM-based learning” affect “pupils’ CTs”?	
RQ 2	What factors influence the success of “STEM education” in improving “CTs”?	
Criteria	Inklusif	Eksklusif
1.	Articles from the past 5 years (2021–2026)	Articles published before 2021
2.	The content type is a journal article	Articles unrelated to STEM in education and CTs
3.	Journal article type: research article	Reputable international books and journals, excluding those published by Elsevier, MDPI AG, and IEEE, and not classified as open access.
4.	Leading global publications sourced from both Scholarly Google and Scopus	

Analysis in this study was performed in the following steps: (1) selection and screening of articles, (2) collection of information, or (3) integration of results. The article screening process adhered to PRISMA to ensure a transparent and accountable selection process (Akmal et al., 2025). The collected data included article identifiers, publication platform types, and keywords related to CTs and STEM learning. Of the overall 100 articles obtained (50 from the Google Scholar and 50 from the Scopus) and following a screening process, 15 articles were selected for further analysis

Based on the research questions, a re-selection was conducted using the previously created inclusion and exclusion tables, and visualized using a PRISMA diagram (Aulia & Maryati, 2026). The screening process was carried out by two independent reviewers to ensure the consistency and reliability of article selection. Initially, all identified articles were screened based on titles and abstracts, followed by a full-text review to determine their relevance to the research objectives. Any disagreements between the reviewers regarding article eligibility were resolved through discussion and consensus. In cases where disagreements could not be resolved

directly, a third reviewer was consulted to make the final decision. Furthermore, the data extraction process included information on publication year, research design, sample characteristics, STEM learning model, critical thinking indicators, instruments used, and main findings. To ensure the consistency of the screening process, inter-rater reliability was assessed using percentage agreement between reviewers, which indicated a high level of consistency in the article selection process.

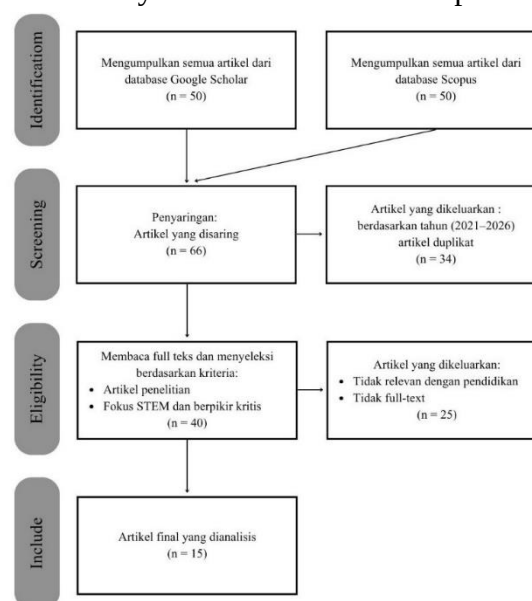


Figure 1. Prism Diagram (Aulia & Maryati, 2026)

RESULTS AND DISCUSSION

Based on the results of the research and related discussions, it was concluded that using STEM learning is effective in enhancing pupils' CTs. This educational approach not only emphasizes mastery of cognitive aspects in understanding the subject matter but also encompasses the holistic development of pupils' skills and attitudes, while fostering social skills

including cooperation, the capacity to express opinions, and the courage to ask questions. Implementing education based on STEM, pupils demonstrate increased engagement and higher motivation in participation in the educational process. Therefore, STEM-based learning is capable of creating a more meaningful learning experience and promoting an overall improvement in CTs.

Table 2. Results of Article Analysis

No.	Author	Year	Research Model	Skills Studied	Research Findings
1.	Mater <i>et al.</i>	2022	STEM-based activities	CTs	The findings show that compared to conventional learning, STEM-based learning has a significant impact on the improvement of pupils' CTs. This is evidenced by a significant difference between the treatment condition and the control condition, in which the condition that implemented STEM received better results in CT.
2.	Adhelacahya <i>et al.</i>	2023	STEM-based PBL	CTs	The research findings indicate a significant improvement in pupils' CTs. This is evidenced by the score of 0.76 on the N-Gain scale, which falls into the high category. It is also evident from the rise in pupils' grades from 66 on the pre-test to 93 on the post-test, indicating a significant improvement following the implementation of STEM education integrated with the PBL model.
3.	Simeon <i>et al.</i>	2022	STEM learning	Design thinking	The findings show that combining STEM with design-based learning has a great impact on pupils' physics grades. This is evident from the improvement in final exam scores compared to initial exam scores, for both male and female pupils.
4.	Oyewo <i>et al.</i>	2022	PjBL STEM	CTs	Research findings indicate that STEM education through water treatment activities can significantly enhance pupils' CTs. These activities, which are based on actual problems, encourage pupils to think analytically, find solutions, and integrate various interdisciplinary concepts.
5.	Minarti <i>et al.</i>	2022	STEM Based Learning Approach	CTs	The findings show that the improvement observed in the treatment group, particularly in terms of CTs, was greater than that observed in the control group. The average CTs score of students in the treatment group increased from 59.2% to 80.4%, while in the treatment group it

					only increased from 46.8% to 65%.
6.	Hasanah <i>et al.</i>	2025	STEM Approach	CT	This study indicates applying the blended-learning strategy of STEM combined with the flipped lesson model method has a positive effect on improving students' CTs in physics. This is supported by the results of the t-test, with significance values of 0.002 and 0.000 (< 0.05), showing a significant difference between the test group and the control group. Furthermore, the improvement in CTs in the treatment group had an N-Gain value of 0.61 and 0.51, which falls into the moderate category, while the control group had an N-Gain value of approximately 0.26–0.30, which falls into the low category.
7.	Komalasari <i>et al.</i>	2024	STEM Learning	CT	The n-gain scores for CTs showed sixteen pupils meeting the moderate criterion and seven meeting the high criterion. This study concluded that STEM learning using a scientific approach influences CTs.
8.	Nurlaila <i>et al.</i>	2026	STEM-based E-LKPD	CTs	The study shows that the results of the CTs effectiveness test for the experimental group using STEM-based digital worksheets showed a significantly higher improvement compared to the control group. This is evidenced by N-Gain values falling within the moderate to high range (0.4–0.8) and a statistical significance level of $p < 0.05$.
9.	Pertiwi <i>et al.</i>	2024	Concept-Based Learning in STEM	CTs	This research shows that the CTs score falls into the critically low category at 79.18%. The N-Gain score of 0.70 is classified as high, using the sample test that produced a statistical probability of 0.023. The results of this research show that STEM education yields better outcomes than conventional education and has demonstrated its effectiveness in enhancing pupils' CTs.

10.	Yennita <i>et al.</i>	2025	SDGs STEM Learning	Based CT	As shown in the journal, SDG-based STEM It has been proven that this approach is far better at improving CTs than more traditional approaches. This is evidenced by the CTs scores in the STEM class, which had an average of 75.26 higher than the conventional class, which had an average of 62.89 as well as improvements across all critical thinking indicators, such as problem comprehension, providing reasons, drawing conclusions, in-depth analysis, and formulating problem-solving strategies.
11.	Khairani <i>et al.</i>	2025	STEM-Based Problem-Based Learning	CT Abilities	This study shows that the implementation of STEM-integrated PBL greatly improves pupils' CTs, as evidenced by an N-gain score of 0.77 which falls into the high range in the experimental class, and a score of 0.52 which falls into the moderate range in the control class. The test results indicate a meaningful difference between the two groups, suggesting that PBL integrated STEM is effective in improving pupils' CTs.
12.	Susiloningsih <i>et al.</i>	2025	STEM Approach	CT	Research shows that science-based learning is far more effective in enhancing pupils' CTs compared to conventional approaches. This is evident from the increase in average scores from 65.4 to 85.6 in the experimental class, whereas in the control class, scores rose only from 64.8 to 72.3, with a significant difference ($p = 0.001$). This improvement occurs because in STEM learning, pupils are actively engaged in solving real world issues, analyzing, evaluating, and developing data-driven solutions through hands-on activities, projects, and collaboration. Thus, STEM learning has proven effective in developing pupils' CT as one of the key

					competencies in 21st-century skills.
13.	Cintamulya <i>et al.</i>	2024	STEM integrated PBL	CT	The research findings indicate that the implementation of STEM education combined in PBL and supported by information literature-based books is effective in enhancing pupils' CTs, as evidenced by achievement levels ranging from good to very good (>60%). In this learning process, students are trained to incorporate aspects of STEM in analyzing real world problems, thereby developing their ability to identify problems, use evidence, draw conclusions, and apply systematic problem-solving strategies. Overall, the integration of STEM and PBL has proven to be effective in optimizing CTs in the learning process.
14.	Cavus <i>et al.</i>	2025	STEM Education	CT	Research from this journal indicates that improvements in pupils' CTs can be observed through the use of STEM education employing a design-based research (DBR) approach, as indicated by the increase in pretest and posttest scores from 2.68 to 2.78. These results suggest that STEM education is more effective in developing pupils' analytical, evaluative, and reasoning skills. Based on these results, it can be inferred that STEM education has a greater impact on optimizing CT compared to other cognitive skills.
15.	Topsakal <i>et al.</i>	2022	Issue-Based STEM Education	CT	The findings show that prior to the intervention (pre-test), the control group and the experimental group did not differ significantly in terms of pupils' CTs, scoring between 3.10 and 3.29 on average, indicating a relatively equal baseline. However, after implementing STEM-based learning (post-test), there was a significant improvement in the experimental group, where the average critical

thinking ability scores increased to 4.07 and 4.24, while the control group only reached 3.38. These findings indicate the significant positive effect of science-based learning in enhancing pupils' CTs compared to conventional learning.

The data in Table 1 indicate that the implementation of STEM education has a largely positive impact on optimizing pupils' CTs. STEM education has significant advantages because it provides pupils with opportunities to develop various abilities, both in cognitive aspects and higher-order thinking skills. Quantitatively, all 15 studies reviewed reported positive improvements in students' critical thinking skills following the implementation of STEM-based learning. Several studies reported N-Gain scores ranging from moderate to high categories, approximately between 0.40 and 0.77, while other studies showed significant increases in post-test scores and statistical significance values of $p < 0.05$. These findings indicate that STEM-based learning consistently contributes to improving students' abilities in analysis, evaluation, reasoning, and problem-solving across various educational contexts. Through integrated activities, pupils are encouraged to analyze, solve problems, and connect concepts with situations in their surroundings, thereby allowing CTs to develop optimally. Furthermore, the reviewed studies involved various intervention models, such as STEM-integrated Problem-Based Learning (PBL), Project-Based Learning (PjBL), flipped classroom, digital worksheets (E-LKPD), and design-based learning, implemented across elementary, secondary, and higher education levels. Therefore, a summary table comparing intervention

type, duration, educational level, critical thinking indicators, and learning outcomes is important to provide a clearer overview of the heterogeneity and effectiveness of STEM interventions. Results of the literature review Mater et al., (2022) demonstrate a significant effect of STEM-based learning on pupils' CTs compared to conventional learning, as evidenced by the differences between the experimental and control groups, in which students in the STEM group achieved higher CT outcomes.

Research (Adhelacahya et al., 2023; Oyewo et al., 2022; Simeon et al., 2022) indicates a significant improvement in CTs, as evidenced by a high N-Gain score of 0.76. Student scores also showed a significant increase from 66 on the pretest to 93 on the posttest, indicating a significant improvement following the implementation of STEM learning integrated with PBL. However, the findings across these studies also demonstrate a degree of heterogeneity that may be influenced by several factors, including differences in critical thinking measurement instruments, study quality, and cultural or curriculum contexts. Some studies measured CT using standardized critical thinking tests, while others employed project assessments, observation sheets, or problem-solving tasks, which may produce variations in reported outcomes. In addition, differences in research design, sample size, duration of intervention, and implementation quality

may also affect the magnitude of the reported improvements. Variations in educational contexts, such as curriculum characteristics, learning environments, and students' prior experiences with STEM learning in different countries or educational levels, may further contribute to the differences in research findings. From these three studies, it can be concluded that there is an improvement in CTs through STEM-based learning that involves meaningful activities. Activities based on real-world problems encourage pupils to think analytically, find solutions, and integrate various interdisciplinary concepts. Additionally, the integrated learning process provides pupils with opportunities for exploration, experimentation, and collaborative discussion, thereby enhancing their ability to evaluate information, make decisions, and present arguments logically. Thus, STEM-based learning not only enhances conceptual understanding but also develops higher-order thinking skills essential for addressing everyday challenges.

Research by Minarti et al., (2022) showed a greater improvement in CTs in the experimental class compared to the control class. The improvement in CTs in the experimental class averaged 59.2% to 80.4%, while in the control class, the improvement was only 46.8% to 65%. Research by Hasanah et al., (2025) demonstrates a significant effect on the improvement of pupils' CTs in physics learning through the application of a STEM approach integrated with the flipped classroom model. This was proven through the results of a statistical test (independent t-test) with significance values of 0.002 and 0.000 (< 0.05); these results indicate a difference between the experimental class and the control class. Furthermore, the

improvement in CTs in the experimental class, at 0.61 and 0.51, falls into the moderate category, whereas in the control class, around 0.26–0.30, it falls into the low category.

Research (Komalasari et al., 2024; Nurlaila et al., 2026; Pertiwi et al., 2024) indicates N-gain scores in the moderate to high range regarding the improvement of CTs. This study concludes that STEM learning using a scientific approach influences CTs. All three studies demonstrate an improvement when STEM learning is implemented. The results of STEM learning are higher compared to conventional learning and are effective in optimizing pupils' CTs through activities that develop these skills. This STEM learning transforms pupils from mere concept readers into problem investigators and solution designers. Through activities such as analyzing local pollution data and designing campaigns, they directly apply their analytical, evaluative, and synthetic skills to authentic issues. This aligns with the principles of Place-Based Education, where learning connected to pupils' immediate realities fosters deeper and more meaningful understanding.

Research by Yennita et al., (2025) demonstrates that SDG-based STEM learning is significantly more effective than conventional methods in optimizing pupils' CTs. It was proven that STEM classes had an overall CTs rating of 75.26, which is higher than that of the conventional class at 62.89, as well as improvements across all critical thinking indicators, such as the ability to understand problems, provide reasons, draw conclusions, analyze in depth, and formulate problem-solving strategies. A study from Khairani et al., (2025) demonstrates implementation of student-centered learning integrated with

STEM significantly enhances pupils' CTs. This is evidenced by the N-gain score of the experimental class at 0.77, which falls into the high category, while the control class's score of 0.52 falls into the moderate category. These results indicate a significant difference between the two groups. Thus, STEM-based PBL is effective in developing pupils' CTs.

Research by Susiloningsih et al., (2025) shows Learning based on STEM is far better at improving students' CTs than more traditional teaching methods. This is evidenced by an increase in the average score in the experimental class from 65.4 to 85.6, whereas in the control class it only increased from 64.8 to 72.3, with a significant difference ($p = 0.001$). This improvement occurred because in STEM learning, pupils are actively engaged in real-world problem-solving, analysis, evaluation, and the development of data-driven solutions through hands-on activities, projects, and collaboration. The study indicates that STEM learning, when implemented using experimental methods, encourages pupils to engage in group-based (collaborative) learning activities, ensuring all pupils are actively involved in the learning process within a fun and engaging environment. Such high levels of learning activity contribute to improving pupils' CTs. Thus, STEM learning has proven effective in developing pupils' CTs as part of 21st-century skills.

Research by Cintamulya et al., (2025) shows that the implementation of STEM learning integrated with PBL and supported by information literacy-based e-books effectively enhances pupils' CTs, as evidenced by achievement levels ranging from good to very good (>60%). In this learning process, pupils are trained to integrate aspects of science, technology,

engineering, and mathematics in analyzing real-world problems, thereby developing the ability to clarify problems, use evidence, draw conclusions, and employ systematic problem-solving strategies. Research by Çavuş et al., (2025) indicates an improvement in pupils' CTs through the implementation of STEM-based learning using the Design-Based Research (DBR) approach, as evidenced by an increase in pretest scores from 2.68 to 2.78 on the posttest. These results suggest that STEM learning is effective in developing pupils' analytical, evaluative, and reasoning skills.

Research by Topsakal et al., (2022) shows that prior to the intervention (pretest), there was no significant difference between the control and experimental groups in terms of pupils' CTs, with average scores ranging from 3.10 to 3.29, indicating relatively equivalent baseline conditions. However, after the implementation of STEM-based learning (posttest), there was a significant improvement in the experimental group, where the average critical thinking scores increased to 4.07 and 4.24, while the control group only reached 3.38. These research results indicate a significant positive effect on the improvement of pupils' CTs through STEM learning compared to conventional learning. It can be concluded that integrating the STEM approach into the learning process is an effective and relevant method for optimally improving the quality of pupils' CTs.

CONCLUSIONS

Based on a review of the literature, preliminary evidence suggests that STEM-based learning is effective in improving students' critical thinking skills through problem-solving activities, projects, and contextual learning. However, the quality

and characteristics of the reviewed studies varied in terms of research design, sample size, intervention duration, and critical thinking assessment instruments; therefore, the findings should be interpreted cautiously and further high-quality research is still needed to strengthen the evidence. Previous research has largely focused on the final outcomes of students' CTs and has not yet examined in depth the students' thought processes during the learning process.

Furthermore, most studies have primarily emphasized cognitive aspects, so the impact of STEM education on other 21st-century skills such as creativity, collaboration, and communication remains largely unexplored. The variety of models, media, and contexts used in STEM learning is also still limited to specific subjects.

Therefore, future research needs to develop more diverse and in-depth STEM implementations to provide a more comprehensive picture of the impact of STEM learning on students' learning processes. In practical and policy contexts, it is recommended that educational institutions integrate STEM teacher training modules that emphasize critical thinking scaffolding strategies, inquiry-based learning, and authentic problem-solving activities. In addition, the development of standardized critical thinking assessment instruments is necessary to support more consistent evaluation of STEM-based learning programs across different educational contexts.

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