JINEA Journal of Innovation in Education and Learning
Volume 1, No. 1, February 2025
p-ISSN XXX-XXX
e–ISSN XXX-XXX
https://jurnal.ihsancahayapustaka.id/index.php/jinea

STEM Digital Collaboration to Enhance Critical Thinking Skills of Secondary School Students: A Literature Review

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Article Info

Article history:

Received Jan 24, 2025
Revised Feb 16, 2025
Accepted Feb 28, 2025

Keywords:

STEM Education;
Digital Collaboration;
Critical Thinking;
Secondary School Students;
Technology Integration.

Abstract

This literature review explores the role of STEM digital collaboration in enhancing critical thinking skills among secondary school students. As global demands for higher-order cognitive abilities intensify, integrating digital tools within STEM education has emerged as a promising approach to foster interactive, collaborative, and contextually meaningful learning experiences. The review synthesizes recent empirical studies and theoretical perspectives, highlighting innovative pedagogical models such as STEM-Blended Learning, Project-Based Learning, and STEM-based digital modules that effectively cultivate critical thinking. Notably, this study advances the understanding of how balanced technology integration, coupled with collaborative STEM activities, optimizes cognitive skill development while mitigating risks of overdependence on digital resources. The novelty of this review lies in its comprehensive focus on digital collaboration as a catalyst for critical thinking enhancement, bridging theoretical frameworks and practical applications in diverse secondary education contexts. Implications for educators and policymakers emphasize the strategic adoption of integrated STEM-digital pedagogies to prepare students for complex 21st-century challenges. Future research directions include evaluating cross-cultural effectiveness and addressing implementation barriers in technology-supported STEM collaboration.

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How to Cite:
Fatqurhohman, F., Syam, H., Puspitasari, R., Niam, F., & Surur, A.M. (2025). STEM Digital Collaboration to Enhance Critical Thinking Skills of Secondary School Students: A Literature Review. *JINEA: Journal of Innovation in Education and Learning*, *1(1), 37-50*.

1. INTRODUCTION

In the modern education era, critical thinking skills have become an essential competency that students must possess to face the challenges of the 21st century (Mao et al., 2022; Saleh, 2019). Critical thinking enables students to analyze information logically, evaluate arguments, and make decisions based on valid evidence (Siahaan, Muhammad, Dasari, et al., 2023). However, studies indicate that developing this skill remains challenging, particularly in developing countries, due to the dominance of traditional teaching approaches that insufficiently encourage optimal intellectual exploration among students (Hunaidah et al., 2018; Widana, 2018). Therefore, strengthening critical thinking requires serious attention in curriculum design and teaching strategies.

Collaborative learning is an effective approach to enhancing students' critical thinking skills. This approach emphasizes cooperation among students to achieve shared goals through active interaction and discussion, thereby creating an inclusive and interactive learning environment (Liao & Wu, 2022; Warsah et al., 2021). Exposure to diverse perspectives encourages students to consider different viewpoints before reaching consensus, which strengthens critical thinking abilities. Moreover, collaborative learning provides opportunities for active engagement, boosts self-confidence, and honest communication skills (Smith, 2020; Supena et al., 2021).

The combination of critical thinking and collaborative learning has proven effective in improving student learning outcomes. Research by (Gaskins-Scott, 2020; Smith, 2020) reveals that students learning in collaborative environments exhibit higher critical thinking abilities and a deeper understanding of concepts compared to those learning individually. Additionally, this method enhances communication and teamwork skills, which are key competencies in addressing the dynamics of the modern world. Thus, integrating collaborative learning into education becomes an important strategy for optimally developing students' critical thinking skills.

In modern education contexts, integrating technology into collaborative learning plays a vital role in supporting effective learning processes. Digital platforms such as online discussion forums and collaboration software enable students to work together across geographical boundaries, broaden perspectives, and gain insights from diverse cultural backgrounds (Hamengkubuwono et al., 2022; Kim et al., 2022). This aligns with global needs to improve digital literacy and higher-order thinking skills (Alsaleh, 2020). Nevertheless, implementing collaborative learning that focuses on developing critical thinking requires careful planning to ensure tasks promote deep analysis and equitable participation. Studies show that collaborative learning enhances students' analytical and communication abilities, although challenges remain, such as insufficient teacher training and unbalanced group dynamics (Hsu, 2021; Kusumawati et al., 2019; Warsah et al., 2021).

STEM education (*Science, Technology, Engineering, and Mathematics*) is increasingly recognized as an effective approach to preparing students for 21st-century challenges by emphasizing the development of critical thinking skills (Fatqurhohman et al., 2020; Syam et al., 2020). Critical thinking, which involves the ability to analyze and make decisions based on rational considerations, is a fundamental skill in modern education (Fatqurhohman, 2025). Interdisciplinary, problem-solving-oriented STEM learning is believed to encourage analytical thinking and the development of practical skills through inquiry-based and experiential approaches (Haryanto et al., 2024; Pratama et al., 2025). However, despite its growing adoption, empirical evidence regarding STEM's effectiveness in enhancing critical thinking remains limited and requires further investigation (Ramdani et al., 2022; Syam et al., 2020; Tang et al., 2020).

Traditional learning methods, which emphasize memorization and theory, are often criticized for inadequately fostering critical thinking and problem-solving skills (Abdulah et al., 2021; Frenanto et al., 2023; Tang et al., 2020). In contrast, STEM education encourages active participation, experimentation, and knowledge application in practical contexts. Nonetheless, empirical evidence on STEM's impact on critical thinking is still sparse and inconclusive, partly due to variations in implementation levels and educational contexts (Bertrand & Namukasa, 2023; Haryanto et al., 2024). Therefore, further research is necessary to fully understand the cognitive development effects of this approach.

Numerous studies indicate that STEM-based education is increasingly being implemented to improve learning quality in the modern era. However, literature reviews reveal gaps concerning empirical evidence specifically assessing STEM's impact on students' critical thinking abilities. Most research focuses more on student engagement, interest in STEM fields, or general academic achievement, while in-depth analyzes of STEM's contribution to developing critical thinking remain limited (Fuchs et al., 2018). This highlights the need for more systematic reviews to understand how STEM components, including inquiry-based approaches, collaborative problem-solving, and interdisciplinary integration, can facilitate critical thinking skills.

This study aims to review and synthesize findings related to the influence of STEM-based learning on high school students' critical thinking abilities, comparing it with traditional teaching methods. The primary focus is to evaluate the extent to which STEM approaches enhance students' analytical, reasoning, and complex problem-solving skills (Hasanah et al., 2021; Permatasari et al., 2025; Ramadani et al., 2025). Additionally, this study identifies the most effective STEM learning factors for developing critical thinking skills based on recent literature. Utilizing a literature review methodology, the research also examines trends, challenges, and recommendations for optimizing STEM education, particularly through digital collaboration.

The main research question addressed is: How does STEM-based learning influence high school students' critical thinking abilities compared to traditional methods? This review is relevant to supporting educational transformation that adapts to 21st-century demands by emphasizing critical thinking as a core competency. The findings are expected to strengthen theoretical foundations and provide practical recommendations for educators and policymakers in implementing effective and sustainable STEM learning.

2. METHOD

This study employs a qualitative approach using a narrative literature review method to explore strategies for integrating STEM-based digital collaboration to enhance critical thinking skills among secondary school students. The literature review approach was chosen as it allows for an in-depth analysis of various academic studies and up-to-date references relevant to the topic, while providing space for a comprehensive and thematic conceptual synthesis (Snyder, 2019).

2.1. Literature Search and Scope

The literature for this study was systematically retrieved from several leading academic databases Google Scholar, covering publications from 2019 to 2024. The search was conducted between January and March 2025 using the following Boolean keywords:

"STEM education" AND "digital collaboration" AND "critical thinking" AND "secondary school".

Additionally, keyword variations such as online collaboration, virtual teamwork, and 21st-century skills were employed to capture a broader and more contextual range of perspectives.

2.2. Inclusion and Exclusion Parameters

To ensure the relevance and quality of the literature, this study established the following inclusion and exclusion criteria:

Table 1. Criteria Inclusion and Exclusion

Criteria	Description
Inclusion Criteria	▪ Peer-reviewed journal articles, books, and research reports published between 2019 and 2024 ▪ Studies focusing on the secondary school level (ages 12–18) ▪ Literature explicitly addressing the integration of STEM, digital collaboration, and critical thinking skills.
Exclusion Criteria	▪ Studies exclusively related to primary or higher education levels ▪ Publications that do not discuss critical thinking skills within the context of STEM education.

2.3. Data Collection and Selection Process

The literature data collection was conducted through stages of identification, selection, and synthesis. During the identification phase, articles matching the predetermined keywords and publication period were gathered. The selection phase involved reading abstracts and full texts to ensure compliance with the inclusion and exclusion criteria. Literature that met these criteria was then classified according to main themes such as key elements in STEM-based digital collaboration, design of discussion, and problem-based tasks, and the role of technology in supporting student collaboration (Nurazmi & Bancong, 2021; Rahayu et al., 2023).

2.4. Data Analysis

Data analysis employed a thematic analysis method aimed at grouping and interpreting information based on the major themes emerging from the literature. The analysis process consists of:

1) Exploratory reading to identify recurring and relevant themes.
2) Thematic clustering into conceptual groups, including:
   - Models and frameworks of STEM-based digital collaboration.
   - Digital tools and platforms for collaborative STEM learning.
   - The impact of digital collaboration on the development of critical thinking skills.

- Challenges and future directions for development.

3) Cross-source synthesis to critically compare theoretical arguments and empirical findings (Braun & Clarke, 2019).

This approach facilitates an in-depth connection between educational theories, such as social constructivism and inquiry-based learning, and their practical applications in technology-mediated STEM education.

2.5. Novelty of Method

Unlike previous literature reviews that tend to address STEM pedagogy or technology use separately, this study deliberately integrates pedagogical theories with the affordances of digital technologies to position digital collaboration as a primary catalyst for developing critical thinking skills. This context-rich narrative approach offers deep interpretative insights and broader educational implications, moving beyond mere descriptive summaries (Snyder, 2019; Cooper, 2015).

3. RESULTS AND DISCUSSION

3.1. Results

The following is a table containing 10 selected articles from various references related to research on improving critical thinking skills through collaborative learning in the context of education in Indonesia. These articles were selected based on relevance, quality of sources, as well as academic contributions in the last five years (2019–2024).

Table 2. Literature Review

No	Author	Theme/Topic	Result
1	Sumarni & Kadarwati (2020)	The influence of ethno-STEM project-based learning on critical and creative thinking skills	Ethno-STEM project-based learning enhances high school students' critical and creative thinking skills.
2	Haryadi, Situmorang, & Siahaan (2021)	Implementation of STEM-Blended Learning to improve higher-order thinking skills on the concept of Kepler's Laws during the COVID-19 pandemic.	The implementation of STEM-Blended Learning is effective in improving students' higher-order thinking skills on the concept of Kepler's Law during the COVID-19 pandemic.
3	Siahaan et al. (2022)	Integrasi Problem-Based Learning dalam pendidikan STEM untuk meningkatkan literasi lingkungan siswa	Integration of Problem-Based Learning in STEM education to improve students' environmental literacy
4	Smith et al (2022)	Principles of Problem-Based Learning in STEM education based on expert insights and research	Four key principles of PBL in STEM education: flexible knowledge, active metacognitive thinking, intrinsically motivated collaboration, and problems embedded in real contexts.

5	Yulkiffli et al. (2022)	Implementation of STEAM-Integrated Project-Based Learning to improve students' creative and collaborative thinking skills.	STEAM-Integrated Project-Based Learning is effective in improving students' creative and collaborative thinking skills.
6	Yani (2023)	Development of STEM-based e-modules to improve students' critical thinking skills in economics learning.	STEM-based e-modules are effective in improving students' critical thinking skills in economics learning.
7	Situmorang & Haryadi (2023)	Implementation and role of STEM Integrated Problem-Based Learning in science learning.	STEM Integrated Problem-Based Learning is effective in improving students' understanding of science concepts and critical thinking skills.
8	Pramasdyahsari et al. (2023)	Development of STEM-PjBL based digital books to improve students' critical mathematical thinking skills	STEM-PjBL based digital books are effective in improving junior high school students' critical thinking skills in mathematics.
9	Hakim et al. (2023)	Implementation of the CTL approach in STEM learning to improve critical thinking skills	The CTL approach in STEM learning can improve students' critical thinking skills through observation, hypothesis, and investigation.
10	Fior et al. (2024)	Digital technology-based STEM learning experiences in schools	The use of digital technology in STEM learning enhances students' collaboration, creativity, critical thinking, experimentation, prototyping, communication, and problem-solving skills.

The study by (Haryadi et al., 2021) demonstrates that the implementation of the STEM-Blended Learning model effectively enhances students' higher-order thinking skills on the concept of Kepler's Laws during the COVID-19 pandemic. This model integrates online and offline learning, enabling students to learn independently and collaboratively while developing their critical and analytical thinking abilities. Consistent with these findings, (Yulkifli et al., 2022) developed a STEM-based electronic module that challenges students to analyze and solve economic problems, significantly improving their critical thinking skills. Additionally, (Haryadi et al., 2021) investigated the STEM Integrated Problem-Based Learning model, which combines problem-based learning with STEM concepts, proving effective in improving students' understanding of science and critical thinking skills in a contextual and collaborative manner.

Other studies also support the effectiveness of STEM approaches in learning. For instance, (Siahaan, Muhammad, Dasari, et al., 2023) integrated Problem-Based Learning to enhance students' environmental literacy through real-world problem solving, while (Kim et al., 2022; Smith, 2020) emphasized collaboration, metacognitive thinking, and contextually embedded problems as key principles for developing critical and creative skills. The integration of digital technology, as highlighted by (Hanatan et al., 2023; Muhammad et al., 2022; Setyaningrum, 2020), along with the development of interactive learning media such as STEM-based e-modules and digital books (Huang, 2022; R. N. Sari & Juandi, 2023; Sariningsih et al., 2023), further strengthens students' creativity and critical thinking abilities. Thus, STEM approaches that combine blended learning, project-based learning, and digital technology represent effective strategies to prepare students to face 21st-century challenges with critical, creative, and collaborative thinking.

3.2. Discussion

The Effectiveness of STEM in Enhancing Higher-Order Thinking Skills

This theme highlights the primary goal of STEM education: developing students' critical, analytical, and problem-solving skills. Numerous studies consistently demonstrate that STEM approaches effectively enhance higher-order thinking skills (HOTS). For instance, (Haryadi et al., 2021; Siahaan, Muhammad, & Dasari, 2023) found that the STEM-Blended Learning model significantly improved students' critical thinking in learning Kepler's Law during the COVID-19 pandemic. Likewise, (Alim et al., 2021) developed a STEM-based electronic module that successfully fostered students' critical and creative thinking in economics. In addition, (Bertrand & Namukasa, 2023; Haryanto et al., 2024) reported that a STEM Project-Based Learning (PjBL) digital book substantially increased students' mathematical critical thinking skills. These findings collectively underscore the effectiveness of STEM-integrated learning in nurturing essential cognitive abilities needed for the 21st century. This supports assertion that STEM education plays a vital role in promoting creativity, critical thinking, and problem-solving, competencies indispensable for students to thrive amid complex real-world challenges. Therefore, implementing STEM approaches is crucial in preparing learners to succeed in dynamic and evolving environments.

The Role of Technology in STEM Learning

Integrating technology into STEM education is essential for creating interactive and engaging learning environments that foster critical thinking and creativity, skills highly valued by employers(Liston et al., 2022; Wu et al., 2023). Digital tools enhance collaboration and practical problem-solving, effectively bridging the gap between theoretical knowledge and real-world application, emphasize that technology supports not only communication and teamwork but also experimentation, prototyping, and critical thinking skills among students. Similarly, (Hamdan & Saripudin, 2023; Ramdani et al., 2022; J. Sari, 2021; Tang et al., 2020) developed STEM-based e-modules that provide interactive learning experiences, encouraging students to apply creative thinking in solving complex STEM problems. These innovations promote deeper engagement and the development of crucial 21st-century competencies. However, technology integration must be balanced with traditional instructional methods to avoid over-reliance, ensuring pedagogical effectiveness. Therefore, a thoughtful and balanced use of digital tools maximizes their benefits while maintaining the quality of STEM education. This approach prepares students to become proficient problem-solvers and innovators ready for future STEM careers.

STEM Learning in the 21st Century

In the rapidly evolving landscape of the 21st century, STEM education plays a vital role in preparing students to address complex global challenges. The transformation in STEM teaching and learning arises from the convergence of educational research, emerging technologies, and innovative classroom practices. This evolution highlights the importance of interdisciplinary approaches and the application of STEM knowledge to real-world problems, equipping students with the skills and mindset required to become future innovators and problem-solvers. Supporting this perspective, (Nurazmi & Bancong, 2021; Smith, 2020) identified four key principles for implementing Problem-Based Learning (PBL) in STEM: the cultivation of flexible knowledge, active metacognitive engagement, collaboration driven by intrinsic motivation, and embedding problems within authentic real-world contexts (Hasanah et al., 2021; Nasir et al., 2022). Furthermore, ethnocultural-based STEM projects (Ethno-STEM) have demonstrated the potential to enhance students' critical and creative thinking skills while simultaneously fostering cultural appreciation and environmental awareness (Noto et al., 2023)).

Contextual and collaborative learning strategies play a vital role in this preparation. (Jia et al., 2023; Mayasari et al., 2022) identified four essential principles for implementing Problem-Based Learning (PBL) within STEM education: flexible knowledge, active metacognitive thinking, collaboration driven by intrinsic motivation, and embedding problems in authentic contexts. These principles foster environments that nurture critical and creative thinking. Complementing this, (Noto et al., 2023) demonstrated that ethnocultural-based project-based learning (Ethno-STEM), which integrates local cultural elements, significantly enhances students' critical and creative thinking skills. This culturally responsive approach not only deepens conceptual understanding but also promotes cultural appreciation and environmental awareness, aligning STEM education with broader social and ecological goals.

These themes collectively underscore the essential dimensions of STEM education: its proven effectiveness in enhancing students' higher-order thinking skills, the pivotal role of technology in enriching the learning experience, and its critical relevance in equipping students to meet the demands of the 21st century. By exploring these interconnected areas, the discussion will offer a holistic understanding of how STEM education not only fosters cognitive development but also prepares learners to navigate and solve complex, real-world problems effectively. Addressing these aspects provides valuable insights into the transformative potential of STEM education in shaping future-ready individuals.

4. CONCLUSION

This study contributes novel evidence demonstrating that the integration of STEM within learning significantly enhances students' higher-order thinking skills, particularly critical thinking, creativity, and problem-solving. Innovative learning models such as STEM-Blended Learning, Project-Based Learning, and STEM-based digital modules have been shown to effectively develop these competencies. Furthermore, the strategic incorporation of digital technology plays a pivotal role in fostering interactive, collaborative learning environments that bridge theoretical knowledge with practical application. Notably, a balanced use of technology alongside traditional instructional methods is essential to maximize educational benefits while preventing excessive dependency.

The findings underscore the importance of implementing integrated STEM approaches supported by digital tools as a vital strategy to prepare students for the complex demands of the 21st century and equip them with relevant skills for future STEM careers. This study's novelty lies in its comprehensive examination of how specific STEM models, complemented by technology, synergistically promote essential cognitive skills in diverse learning contexts.

Implications of this research suggest that educators and educational institutions should adopt integrated STEM frameworks that thoughtfully blend technology with pedagogy to optimize student outcomes. Additionally, ongoing development of interactive digital learning modules tailored to specific educational contexts and learner needs is recommended. For future research, it is advised to investigate the effectiveness of integrated STEM approaches across different educational levels and cultural settings. Moreover, further studies should explore strategies to address potential technical and non-technical challenges in integrating technology within STEM education to ensure sustainable and effective implementation.

ACKNOWLEDGEMENTS

This research was fully self-funded by the author, without financial support from any institution or external funding agency.

DECLARATIONS

Author Contribution	:	Author 1: onceptualization, methodology, data collection, data analysis, writing, original draft; Author 2&5: Data analysis, validation, review, and editing of the manuscript; Author 3&4: Literature review, visualization, and preparation of final manuscript.
Funding Statement	:	This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The study was fully self-funded by the authors.
Conflict of Interest	:	The authors declare that there is no conflict of interest regarding the publication of this paper.

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