Journal of Current Studies in SDGs
Homepage : https://journal.i-ros.org/index.php/JOCSIS
Email : jocsis@i-ros.org

e-ISSN 3089-7564
Vol.1, No.3, August 2025

Application of STEAM Learning to Enhance Students' Critical Thinking Skills

Nur Lailatur Rohmah[1*], Budi Jatmiko[1], Cahyo Febri Wijaksono[2]
[1]Universitas Negeri Surabaya, Surabaya, Indonesia
[2]Universität für Weiterbildung Krems, Krems an der Donau, Austria

DOI : https://doi.org/10.63230/jocsis.v1i3.77

Sections Info
Article history:
Submitted: August 11, 2025
Final Revised: August 17, 2025
Accepted: August 17, 2025
Published: August 27, 2025
Keywords:
21st Century Skills;
Critical Thinking;
Literature Review;
STEAM.

ABSTRACT
Objective: *This study aims to analyze the implementation of the STEAM (Science, Technology, Engineering, Arts, and Mathematics) learning approach in enhancing students' critical thinking skills. The urgency arises from the challenges of the Industrial Revolution 4.0 era in the 21st century, where technological advancement dominates all aspects of human life. However, Indonesia still struggles with low-quality human resources in the face of global competition. Educational reform through innovative learning approaches such as STEAM is therefore essential.* ***Method:*** *This research employed a qualitative approach with a literature study design. Data were collected from various academic sources, including books, journals, and credible scientific publications, which were then analyzed through thematic interpretation to identify the relevance and effectiveness of STEAM in fostering critical thinking abilities.* ***Results:*** *The findings reveal that the STEAM approach is practical in developing students' critical thinking skills by encouraging integrative learning that connects scientific concepts with creativity, problem-solving, and real-world applications. Students engaged in STEAM-based learning show improved reasoning, analytical ability, and adaptability, which are crucial competencies in 21st-century education.* ***Novelty:*** *This study highlights the contribution of STEAM as not only a multidisciplinary learning model but also as an innovative educational reform strategy for Indonesia. By integrating art with science and technology, STEAM offers a holistic framework to prepare students for global challenges while simultaneously strengthening critical thinking as a core competency.*

INTRODUCTION

In the era of industrial revolution 4.0 in the 21st century, all human activities are dominated by high-tech products, as if every human being cannot live without technology. This proves that advances in science and technology are developing very rapidly (Fitriyah & Ramadani, 2021). In this era, developments have a significant impact on various aspects of life, including the education system in Indonesia. Information and communication technology, as well as the boundaries between humans, machines, and other resources, have a strong influence on the education sector (Lase, 2019).

The industrial revolution 4.0 requires quality human resources with 21st-century skills, including critical thinking, creativity, collaboration, and communication abilities. However, it is unfortunate that Indonesia still has a low level of human resources, considering the overall quality of human resources, especially in the face of global competition. Quality human resources come from quality education, in the process of which students are equipped with skills to solve problems, find alternative solutions, and think critically and creatively (Maulana, 2020). One way to achieve this is by optimizing the use of technology in the learning process, so that education can adapt to current developments and contribute to improvements.

"Lifelong education" means that human life cannot be separated from education. In Law No. 20 of 2003 concerning the National Education System, character education

aims to form a strong personality that is in accordance with the identity of the Indonesian nation. The aim of this is to apply the values of character education to students. In this case, it is essential to instill character education, especially in educational institutions, and the nation's noble cultural values must be instilled in every student to prevent a lost generation in terms of national character and culture. At this time, the nation's generation is also faced with moral degradation, which weakens the character of the nation's generation (Purna et al., 2023).

Educational reform is needed to improve the quality of education in Indonesia; this reform includes the development of critical thinking skills (Redhana, 2010). One form of educational reform that can be carried out is by implementing the STEAM (Science, Technology, Engineering, Art, Mathematics) learning approach, which helps educators create experts in various fields. The STEAM learning approach combines the five components of science, namely knowledge, technology, engineering, art, and mathematics.

Research has shown that implementing a STEAM learning approach can help in developing students' knowledge, facilitate exploration through inquiry, and encourage students to create new knowledge (Permanasari, 2016). Implementing this approach is expected to expand students' knowledge, encourage students to explore, and develop creativity and critical thinking skills.

Educators need to use sophisticated technology in the learning process. Implementing the STEAM learning approach can help improve students' critical thinking skills. These five STEAM components can shape students' thinking patterns, including the ability to solve problems, analyze, and relate concepts to surrounding situations (Dhawan, 2020).

In contrast to conventional (traditional) teaching approaches, educators who apply the STEAM framework integrate various scientific disciplines, creating a dynamic synergy between the modeling process and mathematics and science content. With this holistic approach, students can develop both sides of their brain simultaneously. The skills students gain from STEAM learning can be applied in various professions in the future (Zubaidah, 2019).

The implementation of STEAM learning is reflected in several questions related to the implementation of learning, such as learning approaches (student-centered or teacher-centered), implementation of inquiry-based learning, problem-projects, collaboration, integrated learning, adaptation to student needs, as well as evaluation and reflection (Nuragnia & Usman, 2021).

Based on this, it is hoped that this research can improve students' critical thinking skills in facing the Industrial Revolution 4.0. In this case, the use of the STEAM approach provides holistic and integrated learning because it can optimize the use of technology in learning by preparing quality human resources with 21st-century skills.

RESEARCH METHOD

This research uses qualitative research methods, which are included in the type of literature study or literature review. The type of data used in this research is secondary data. Literary studies rely on library sources as the primary source of research data (Jaelani et al., 2020; Said, 2023). References obtained, such as articles and journals used in this research, through searches on the Google Scholar web, Scopus, and other national and international websites. A total of 20 articles were selected for review according to the criteria set by the author.

Library materials obtained from various references are analyzed critically and must be in-depth in order to support the propositions and ideas (Adlini et al., 2022). The research was carried out by identifying problems that occurred in school learning activities. Data is collected from relevant literature and information sources, then analyzed and interpreted to inform a strategy for solving the problem through a literature study.

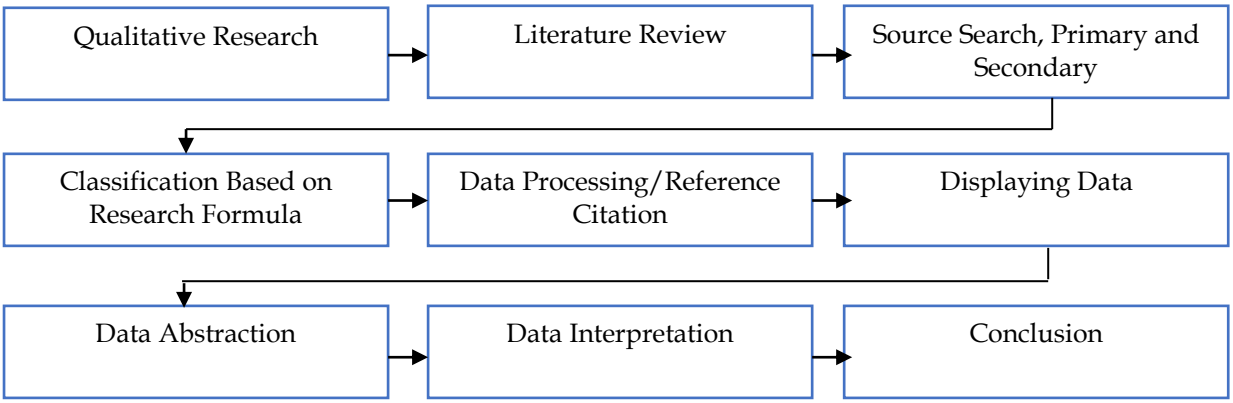

Figure 1. Qualitative research chart of literature study

Figure 1 depicts a qualitative research chart of the library study type. The research steps begin with collecting various literature sources, and then the data is classified based on the research formulation. In the next stage, data processing is carried out and/or references are cited, which are presented as research findings. This information is then abstracted to make it whole and then interpreted to produce knowledge that supports conclusions (Darmalaksana, 2020).

RESULTS AND DISCUSSION

Results

Based on the explanation and methods described above, 20 articles were analyzed, as shown in the Table 1.

Table 1. Results of article analysis

No	Writer	Year	Title	Research result
1	Wasito Utomo, Wiwid Suryono, Jimmi, Tomi Apra Santosa, Ika Agustina	2023	The Effect of STEAM-Based Hybrid Based Learning Model on Students' Critical Thinking Skills	This research examines the influence of a STEAM-based hybrid learning model on students' critical thinking abilities through meta-analysis of 15 national and international journals. Using the PRISMA method, data was taken from sources published in the last 5 years (2018-2023) with an experimental or quasi-experimental design. The results of quantitative analysis using the CMA version 3 application showed a strong average effect size (ES = 1.052, $p < 0.01$). It can be concluded

No	Writer	Year	Title	Research result
				from this article that the STEAM-based hybrid learning model has a significant and higher effect on students' critical thinking abilities than the conventional model.
2	Muhammad Syukri, Zhaifatul Ukhaira, Zainuddin, Fitria Herliana, Nurazidawati Mohamad Arsad	2022	The Influence of STEAM-Based Learning Application on Students' Critical Thinking Ability	This research examines the effect of STEAM-based learning on students' critical thinking abilities. Using a pre-experimental design with pretest-posttest on class XI science students, the results showed a significant increase in critical thinking skills after implementing STEAM. The post-test value showed a significant increase compared to the pretest (Sig. (2-tailed) = 0.000 < 0.05). In conclusion, STEAM-based learning significantly improves students' critical thinking abilities. Researchers suggest further research with a broader and deeper STEAM approach to explore its impact.
3	Agnesi Sekarsari Putri, Zuhdan Kun Prasetyo, Lusila Andriani Purwastuti, Anti-Colonial Prodjosantoso, Himawan Putranta	2023	Effectiveness of STEAM-based blended learning on students' critical and creative thinking skills	This research examines improving students' critical and creative thinking skills through STEAM-based blended learning. With a quasi-experimental design on 180 junior high school students in Yogyakarta, the results showed that STEAM-based blended learning improved students' critical and creative thinking abilities higher than the control class. Analysis using the gain score and Kruskal-Wallis tests showed significant differences between the experimental and control classes. STEAM-based blended learning is recommended as a solution to improve 21st century skills, although this research is limited to one school, so the results may be different in other schools.
4	Alexey A.	2023	Exploring the	This research reviewed 36

No	Writer	Year	Title	Research result
	Chistyakov, Sergei P. Zhdanov, Eleba L. Avdeeva, Elena A. Dyadichenko, Maria L. Kunitsyna, Roza I. Yagudina		characteristics and effectiveness of project-based learning for science and STEAM education	articles about project-based learning (PjBL) in science and STEAM education. The results of the analysis show that PjBL is effective in improving student learning outcomes, problem solving skills and critical thinking. PjBL also increases student motivation and involvement in learning. It is recommended that PjBL be integrated into science and STEAM education at all levels of education as an alternative teaching strategy. However, this research is limited to Eric's database and 36 articles, so further exploration using other databases such as Scopus and Google Scholar is recommended for a more comprehensive study.
5	Virli Dian Putri Aryanti, Gamaliel Septian Airlanda	2024	Development of Interactive STEAM Storybook to Improve Critical Thinking In 3rd Grade	This research develops a STEAM-based storybook for mathematics learning to improve the critical thinking skills of grade 3 elementary school students. The book was rated very good by children's literature experts, media experts and content experts, and practical by students. The t-test results show significant effectiveness with a value of 0.013, which means this book is effective in improving students' critical thinking skills. Therefore, the book "STEAM Activity: The Three Sides of My Family" can be used as an innovative learning medium to improve student learning outcomes.
6	Bayu Murti Suryonegoro, Monica Luishanda Wuryastuti, Nuriana Rachmani Dewi	2024	Literature Review: Inquiry Social Complexity-STEAM Model Based on Math Trail-Virtual Reality Activity Nuanced with Javanese Culture in Improving Critical Thinking Ability	This research analyzes the Inquiry Social Complexity-STEAM model with Math Trail Virtual Reality with Javanese cultural nuances to improve students' critical thinking skills. Using literature review methods and qualitative descriptive analysis, the

No	Writer	Year	Title	Research result
				research found that this model encourages students to discover, investigate, and integrate knowledge, thereby improving critical thinking skills. This model combines elements of social, STEAM, and virtual reality technology in a Javanese cultural context, and is recommended for adoption in mathematics learning. The results show that this model is effective in developing students' critical thinking skills significantly.
7	Nuraini, Nurul Fajri, Indra Himayatul Asri, Edy Waluyo	2023	Development of Project Based Learning With STEAM Approach Model in Improving the Science Literacy Ability of High School Students	This research develops a Project-Based Learning (PjBL) model with a STEAM approach to increase high school students' scientific literacy. Using the Borg & Gall model, validation results from language, material and technology experts show this product is very valid. This product is also considered practical and effective, with effectiveness reaching 88.57%. The effectiveness test shows a significant increase in scientific literacy, with an N-Gain of 0.76 in the high category. The posttest score showed that 91.43% of students obtained a score above 75, indicating an increased ability to explain facts, present hypotheses, and answer questions.
8	Esti Dewi Riyanti, Fenny Roshayati, Veryliana Purnamasari	2020	The Profile of Elementary Teachers' Understanding in STEAM (Science, Technology, Engineering, Art, and Mathematics) Approach	This research analyzes elementary school teachers' understanding of the STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach. Through qualitative descriptive methods with observation, interviews, questionnaires and documentation, it was found that school principals and teachers in Karangrayung Grobogan District did not yet

No	Writer	Year	Title	Research result
				know the STEAM approach. This research aims to develop students' soft skills, cooperation, critical thinking, environmental awareness, responsibility, adaptability and creativity. The results showed a low understanding of STEAM with a mean respondent score of 55.58, highlighting the need for training and outreach regarding this approach.
9	Gamar Al Haddar, Dony Hendriyanto, Haris Munandar, Muhammad Umar Kelibia, Mas'ud Muhammadiah	2023	Analysis of the effectiveness of project STEAM-based learning model to improve students' critical thinking skills	This research examines the influence of the STEAM-based PjBL learning approach on students' critical thinking abilities. Through a quasi-experimental methodology with a non-equivalent control group, it was found that the experimental class that used this approach showed a significant increase in critical thinking abilities compared to the control class. The average posttest score for the experimental class was 74, while the control class was 64. This research recommends that educators optimize learning time and show creativity to increase students' active involvement, as well as looking for projects that are relevant to the real world to be implemented in the STEAM-based PjBL model.
10	DN Ahmad, MM Astriani, M. Alfahnum, L. Setyowati	2021	Increasing Creative Thinking of Students by Learning Organization with STEAM Education	This research analyzes changes in learning before and after using the STEAM method, with a focus on students' creative thinking abilities. The results show that the STEAM method provides a significant positive impact, with an increase in average learning outcomes from 78.26 to 80.52. Hypothesis testing using the t test shows positive changes in students' creative thinking abilities. Thus, the use of the

No	Writer	Year	Title	Research result
				STEAM method in learning is effective in improving students' creative thinking abilities through direct experience in learning projects.
11	Siti Suryaningsih, Fakhira Ainun Nisa, Buchori Muslim, Fauzan Aldiansyah	2022	Learning Innovations: Students' Interest and Motivation on STEAM-PjBL	This research shows that the research instrument is valid and reliable with a reliability value of 0.785 and the data is normally distributed. The use of the STEAM-PjBL method in teaching chemistry in high school produces positive responses from students. The average student interest in learning reached 83.4%, and learning motivation 84.4%, both in the high category. These results indicate that the application of STEAM-PjBL is effective in increasing students' interest and motivation to learn, so that it can be used as innovation in the science learning process.
12	Yuli Rahmawati, Elisabeth Taylor, Peter Charles Taylor, Achmad Ridwan, Alin Mardiah	2022	Students' Engagement in Education as Sustainability: Implementing an Ethical Dilemma-STEAM Teaching Model in Chemistry Learning	This research examines the implementation of the Ethical Dilemma STEAM Teaching Model in secondary schools in Jakarta, which integrates ethical dilemmas into a STEAM project for values-based chemistry learning. This case study shows that this approach is effective in improving students' chemical understanding, critical social thinking, collaborative decision making, and environmental awareness. These results highlight the strategic role of chemistry education in empowering students as agents of change for environmental sustainability. Although limited to the sociocultural context of Jakarta, this research indicates the need for further studies to test the effectiveness of this model in various topics and contexts.
13	Aulia Afia Rochmah,	2023	Science Literacy Ability	This research examines the

No	Writer	Year	Title	Research result
	Aditya Marianti, Nana Kariada Tri Martuti		of High School Students in the Integration of STEAM Learning with Mind Mapping Techniques on Virus Materials	application of STEAM learning with the mind map technique on viral material which is effective in improving the scientific literacy skills of class pre-test. Students' creativity also developed well through making posters and mind maps. Student and teacher responses to this method are positive, indicating effective learning implementation and strong involvement in the learning process.
14	Y. Rahmawati, Adriawati, E Utomo, Mardiah	2021	The integration of STEAM-project-based learning to train students critical thinking skills in science learning through the electrical bell project	This research shows that the integration of STEAM project-based learning (STEAM-PjBL) is effective in training students' critical thinking skills in science learning. Through the electric bell project, students develop a deep understanding of energy transformations, as well as the ability to ask questions, make assumptions, and infer concepts. Key challenges include time management, appropriate project ideas, and student engagement. As a result, 70% of students achieved mastery and competency at the critical thinking level, while the integration of arts in STEAM increased motivation and provided fun learning. Teachers are also encouraged to develop their competencies through various innovative learning approaches.
15	Sri Dwi Indahwati, Fida Rachmadiarti, Eko Hariyono, Binar Kurnia Prahani, Firmanul Catur Wibowo, Muhammad Abd Hadi Bunyamin, Muhammad Satriawan	2023	Integration of independent learning and physics innovation in STEAM-based renewable energy education to improve critical thinking skills in the era of Society 5.0 for Sustainable Development Goals (SDGs) 2030	This research reviews the effectiveness of the integration of Merdeka Learning, Physics Innovation, and the STEAM Approach in Renewable Energy Education to improve students' critical thinking skills in the Society 5.0 Era, in line with SDG 2030. The results show that this approach is effective in increasing students' understanding and critical

No	Writer	Year	Title	Research result
				thinking skills about renewable energy . This integration supports active, experimental and contextual learning, and prepares students to become agents of change in sustainable development. Recommendations include teacher training, facility improvements, collaboration with industry, and an emphasis on assessing critical thinking skills and innovative projects.
16	S Wahyuningsih, NE Nurjanah, UEERasmani, R. Hafidah, AR Pudyaningtyas, MM Syamsuddin	2020	STEAM Learning in Early Childhood Education: A Literature Review	Based on this literature review, the integration of STEAM (Science, Technology, Engineering, Arts and Mathematics) learning in early childhood education has proven to be effective in developing the 21st century skills that children need. STEAM encourages creativity, problem solving, scientific inquiry, and critical thinking. STEAM experiences also increase children's self-confidence and make them more active and able to take initiative in learning. The addition of the 'Arts' element in STEAM provides opportunities for children to describe STEM concepts creatively. 21st century education must continue to innovate, especially in early childhood education, to answer the challenges of the digital era 4.0.
17	Ratih Permana Sari, Hanifah Putri, Mauliza, Sri Setiawaty	2024	Implementation of Project Based Learning Model Integrated STEAM Approach to Improve Students Critical Thinking	This research aims to determine the improvement of students' critical thinking skills through an integrated project-based learning (PjBL) model with the STEAM approach in class X SMA Negeri 2 Langsa. The research results showed that the experimental class that applied the PjBL-STEAM model experienced a

No	Writer	Year	Title	Research result
				significant increase in critical thinking skills with an N-gain value of 0.88 (high category), compared to the control class which had an N-gain of 0.49 (medium category). . Hypothesis testing shows significant differences between the two classes (tcount > ttable, 13.09 > 2.052). The implementation of this model was carried out very well, with an average implementation percentage above 91%.
18	Yetty Isna Wahyuseptiana, Dina Pertiwi Aje, Paulus Widjanarko	2022	STEAM Approach to Improving Critical Thinking Skills in Early Children	This research shows that the application of the STEAM approach can develop critical thinking skills in young children at the Aisyiyah Al Amin Bibis Kindergarten, Surakarta City. The STEAM approach creates an active learning atmosphere and encourages two-way communication, helping children respond and adapt to changes in their environment. However, many 5-6 year olds still need help understanding this approach, and educators need a deeper understanding to implement it effectively. Factors such as family upbringing also influence the development of children's critical thinking. Implementing STEAM requires teachers to be creative and innovative in designing learning.
19	Merri Sri Hartati, Irmaning Rahayu, Kashardi	2023	Critical Thinking Ability Using STEAM-Based PBL Learning at Junior High School Students	This research shows that the STEAM-based Problem Based Learning (PBL) model is more effective in improving students' critical thinking skills compared to conventional learning at SMP Negeri 14 Bengkulu City. The results of the ANOVA test showed a significant value of 0.000 (sig < 0.05), indicating a significant difference in critical thinking abilities between groups that

No	Writer	Year	Title	Research result
				used STEAM-based PBL and those that did not. This research suggests the development of STEAM-based PBL in other subjects, because this research only focuses on biology material.
20	Anik Twiningsih, Evi Elisanti	2021	Development of STEAM Media to Improve Critical Thinking Skills and Science Literacy: A Research and Development Study in SD Negeri Laweyan Surakarta, Indonesia	This research aims to develop STEAM-based learning media to improve the critical thinking skills and scientific literacy of grade 1 students at State Elementary Schools in Laweyan, Surakarta. Using the ADDIE design, this research found that the use of this media increased the average critical thinking ability from 74.80 to 86.67, and scientific literacy from 73.61 to 88.67. The STEAM-based media developed has proven to be effective in improving students' critical thinking skills and scientific literacy, as well as having a positive impact on their learning outcomes.

Based on this table, several articles have been reviewed that focus on the integration of various STEAM (Science, Technology, Engineering, Arts, and Mathematics) learning approaches to improve students' critical thinking abilities. From the 20 articles reviewed, it was found that learning models such as hybrid learning, blended learning, and Project-Based Learning (PBL) were integrated with the STEAM approach.

These studies used a variety of experimental designs, including pretest-posttest and quasi-experiments, and demonstrated consistent results with significant improvements in critical thinking skills and scientific literacy. Data analysis using various statistical methods, such as effect size, t-test, ANOVA, and N-Gain, also showed significant differences between the experimental class that applied the STEAM approach and the control class.

Recommendations from these articles include the need for further development in a broader and deeper STEAM approach, integration of various elements such as local culture, virtual reality technology, mind maps, and art in STEAM learning, as well as training and outreach for educators to implement this approach effectively and innovatively in the learning process.

Implementation of this learning model not only increases critical thinking skills but also students' motivation, involvement, and interest in learning. This is reflected in various studies examining the effectiveness of STEAM in various contexts, including early childhood education, secondary education, and higher education (Chistyakov et al., 2023) (Aryanti et al., 2024).

Discussion

The results of this literature review consistently demonstrate that the STEAM learning approach contributes significantly to the development of students' critical thinking skills across various educational contexts. Several studies indicate that the integration of STEAM in hybrid, blended, and project-based learning (PjBL) models provides a more engaging and meaningful learning experience compared to conventional methods. For example, Utomo et al. (2023) confirmed that a hybrid STEAM-based learning model yields a strong effect size in enhancing critical thinking skills. Similarly, Putri et al. (2023) showed that STEAM-based blended learning not only improves critical thinking but also enhances creative thinking, thereby preparing students with broader 21st-century competencies.

Another consistent finding is the effectiveness of STEAM in cultivating students' scientific literacy. Nuraini et al. (2023) reported that PjBL combined with STEAM significantly improves students' ability to analyze, hypothesize, and communicate scientific concepts. This is in line with Rochmah et al. (2023), who found that integrating STEAM with mind mapping techniques on virology materials led to stronger literacy and student engagement. These results highlight that STEAM does not merely emphasize disciplinary knowledge, but also integrates cross-disciplinary and practical skills necessary for complex problem-solving.

Moreover, STEAM's emphasis on creativity and inquiry provides a holistic framework for learning. The integration of art into STEM disciplines allows students to explore innovative solutions while maintaining scientific rigor (Zubaidah, 2019). The role of inquiry and exploration has also been emphasized by Permanasari (2016), who stressed that STEAM encourages learners to construct new knowledge through active investigation. This is especially relevant in the era of Industrial Revolution 4.0, where critical thinking and creativity are vital for global competitiveness (Lase, 2019).

The studies also reveal variations in teachers' readiness to implement STEAM. Riyanti et al. (2020) found that many elementary teachers still lack sufficient understanding of the STEAM approach, with limited exposure and training. This implies that for STEAM to be effective, professional development programs for educators are crucial. Teacher training in STEAM not only increases their pedagogical capacity but also ensures consistent classroom practices that stimulate critical thinking (Nuragnia & Usman, 2021).

In early childhood contexts, STEAM has been proven to nurture foundational skills such as creativity, problem-solving, and initiative-taking. Wahyuningsih et al. (2020) emphasized that STEAM-based activities allow children to explore their environment while actively enhancing their self-confidence. However, Wahyuseptiana et al. (2022) highlighted challenges, noting that many young children still require guidance to fully benefit from STEAM activities, indicating the need for teacher adaptability and innovation.

From a socio-cultural perspective, recent works have expanded the STEAM framework by integrating local culture and digital technologies. Suryonegoro et al. (2024) demonstrated that a culturally nuanced STEAM model using virtual reality and math trails effectively promotes critical thinking while preserving cultural identity. Likewise, Rahmawati et al. (2022) integrated ethical dilemmas in chemistry learning within the STEAM framework, enhancing students' moral reasoning, collaborative skills, and awareness of sustainability issues. These innovative adaptations show the

flexibility of STEAM in addressing both global educational goals and local contextual needs.

Finally, the consistent positive outcomes across the reviewed studies align with broader calls for educational reform in Indonesia. By equipping students with critical thinking, creativity, collaboration, and communication skills, STEAM emerges as a transformative pedagogical strategy that directly supports the development of human resources capable of thriving in the 21st century (Redhana, 2010; Dhawan, 2020). Nevertheless, challenges such as teacher preparedness, limited resources, and contextual adaptation remain key issues to be addressed in future implementations.

CONCLUSION

Fundamental Finding: Based on the literature review of 20 relevant articles, the application of the STEAM learning approach in various models such as hybrid learning, blended learning, and Project-Based Learning (PBL) has been consistently proven to improve students' critical thinking skills and scientific literacy. These findings emphasize the importance of STEAM as an educational reform strategy to create interactive, integrative, and innovative learning environments that align with the demands of 21st-century education. **Implication:** The consistent effectiveness of STEAM indicates that it can serve as a transformative pedagogical framework for Indonesian education, addressing the challenge of low-quality human resources in facing global competition. Its multidisciplinary nature, integrating science, technology, engineering, arts, and mathematics, contributes not only to cognitive development but also to the holistic formation of students' problem-solving, creativity, and collaboration skills. **Limitation:** This study is limited to a literature review design, which relies on secondary sources rather than primary data. The analysis, although comprehensive, may not fully capture contextual differences across diverse educational settings. Furthermore, the scope is confined to previously published research, which may restrict insights into recent or ongoing innovations in STEAM practice. **Future Research:** Further studies should explore the integration of cultural elements, advanced technology, and creative arts within the STEAM framework to enhance its adaptability and relevance in various educational levels. Empirical research using experimental or mixed-method approaches is recommended to validate the effectiveness of STEAM in specific contexts, ensuring its sustainable application in improving students' critical thinking and broader 21st-century competencies.

AUTHOR CONTRIBUTIONS

Nur Lailatur Rohmah contributed to the conceptual framework, research design, methodology development, data analysis, and drafting of the manuscript. **Budi Jatmiko** contributed to validation, supervision, and sourcing references. **Cahyo Febri Wijaksono** contributed to critical review, and refinement of the manuscript. All listed authors have reviewed and approved the final version of this submission.

CONFLICT OF INTEREST STATEMENT

The authors confirm that there are no conflicts of interest, either financial or personal, that may have influenced the content or outcome of this study.

ETHICAL COMPLIANCE STATEMENT

This manuscript complies with research and publication ethics. The authors affirm that the work is original, conducted with academic integrity, and free from any unethical practices, including plagiarism.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors acknowledge the use of digital tools, including AI-based technologies, as support in the research and writing stages of this article. Specifically, Mendeley was employed for reference management and citation formatting, Grammarly assisted with language refinement and proofreading, and ChatGPT (OpenAI) supported in structuring abstracts, conclusions, and enhancing academic clarity. All outputs generated with digital assistance were critically evaluated and revised to ensure academic rigor and ethical standards were upheld. The final responsibility for the manuscript rests entirely with the authors.

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***Nur Lailatur Rohmah**
Department of Physics Education, Faculty of Mathematics and Natural Sciences, State University of Surabaya
St. Ketintang, Surabaya, East Java, 60231, Indonesia
Email: nurlailatur.21047@mhs.unesa.ac.id

Budi Jatmiko
Department of Physics Education, Faculty of Mathematics and Natural Sciences, State University of Surabaya
St. Ketintang, Surabaya, East Java, 60231, Indonesia
Email: budijatmiko@unesa.ac.id

Cahyo Febri Wijaksono
Universität für Weiterbildung Krems
Dr.-Karl-Dorrek-Straße 30, 3500 Krems an der Donau, Austria
Email: cahyofebri06@gmail.com