

Integrating STEM & STEAM Education to Create Innovative Learning in the Digital Era

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Abstract: The rapid development of digital technology has increased the need for innovative and relevant learning that equips students with 21st-century competencies. STEM (Science, Technology, Engineering, and Mathematics) and STEAM (Science, Technology, Engineering, Arts, and Mathematics) provide interdisciplinary approaches that connect knowledge with authentic problems and projects. This article examines the role of STEM/STEAM integration in creating innovative learning and fostering students' critical thinking, creativity, collaboration, communication, and problem-solving skills. A literature review was conducted by analyzing relevant scientific publications on STEM and STEAM implementation in education. The findings indicate that STEM/STEAM integration promotes active, contextual, collaborative, and project-based learning. The inclusion of Arts in STEAM provides opportunities for creative expression, design, and innovation, while digital technology supports the connection between theoretical knowledge and practical application. However, successful implementation depends on instructional design, teacher readiness, technological access, learning resources, and appropriate assessment. Therefore, STEM/STEAM integration represents a promising approach to creating meaningful and innovative learning experiences that develop students' 21st-century skills and prepare them to adapt creatively to technological developments and global challenges.

Keywords: STEM; STEAM; innovative learning; digital era; 21st century education.

INTRODUCTION

The development of digital technology has brought about significant changes in various aspects of life, including the education sector. Advances in information technology, the internet, and digital devices are driving the transformation of the education system toward more flexible, interactive, and learner-centered learning. Digital technology no longer serves merely as a learning aid but has also become an integral part of the process of developing the knowledge, skills, and competencies needed in the era of globalization. These technological tools are used throughout the education system to support various forms of educational delivery, ranging from kindergarten to work-based training (Selwyn, 2013). In line with this, Pare & Sihotang (2023) states that adapting to advances in digital technology is essential for individuals to master essential 21st-century skills such as problem-solving, creativity, digital literacy, and collaboration in order to succeed and remain relevant in an environment shaped by the dynamics of the digital age.

Digital transformation in education presents a variety of new challenges, particularly in preparing students for 21st-century learning. Students are expected to master a range of skills relevant to the demands of 21st-century life, both as citizens of their own countries and as global citizens, so that they can lead more functional, adaptive, and meaningful lives (Ginanjar, 2016). These skills are known as the 4C concept: creativity, critical thinking, collaboration, and communication and are essential for preparing 21st century students (Arini Kumala Sari & Winda Trisnawati, 2019). Developing 4C skills requires an innovative, contextual, and real-world problem-solving-oriented learning approach. Therefore, STEM (Science, Technology, Engineering, and Mathematics) and STEAM (Science, Technology, Engineering, Arts, and Mathematics) learning approaches are increasingly being adopted as strategies to improve the quality of learning. Both approaches encourage the integration of various disciplines through activities that require students to think critically, collaborate, communicate effectively, and generate creative solutions to various problems, with the goal of preparing students to compete and be ready to work in their chosen fields (Davidi et al., 2021).

STEM is a learning approach that integrates science, technology, engineering, and mathematics into a unified framework focused on solving real-world problems. This approach aiming to develop critical and analytical thinking skills, as well as technological skills relevant to the needs of the 21st century. As educational demands have evolved to go beyond simply emphasizing students' abilities, the STEAM approach has emerged, adding the arts to STEM. Although the STEM model has established prioritized learning objectives, it does not provide educators with the "methods" to achieve these articulated "goals," and this is where STEAM education plays a role. The integration of the arts into STEAM aims to strengthen students' creativity, innovation, and design skills in order to produce more comprehensive solutions. While STEM focuses on conventional lecture-based teaching, STEAM emphasizes inquiry- and project-based learning strategies, including collaborative learning (Sánchez & Cortés, 2024). Accordingly, the relationship between STEM and STEAM is better understood as one of integration and continuity rather than comparison or developmental progression, in which STEAM builds upon and extends the STEM disciplinary core by incorporating the arts to broaden opportunities for creativity and design. In the digital age, the integration of STEM and STEAM is increasingly relevant because it supports contextual, student-centered, and technology-enhanced learning environments that prepare students to respond to technological developments and the demands of a knowledge-based society.

Wahyuni & Gianyar (2021), reported that STEM and STEAM based learning can improve students' learning outcomes by positioning them as active participants in the learning process. Through exploration, problem-solving, collaboration, and independent conceptual discovery, students can connect theoretical knowledge with practical applications. These findings suggest that STEM/STEAM-based learning can provide more meaningful, engaging, and contextual learning experiences. These results are consistent with research conducted Stohlmann et al., (2012) who emphasized the potential of STEM education to develop higher-order thinking, technological literacy, problem-solving, and students' capacity to generate solutions to complex problems. However, the implementation of these approaches should also consider contextual challenges. Adnyana et al., (2024), highlight persistent challenges in developing 21st-century competencies, including disparities in educational access and quality, learning loss or learning crises, and low levels of student literacy. Therefore, the effectiveness of STEM/STEAM integration depends not only on the interdisciplinary curriculum but also on appropriate pedagogical design, teacher readiness, technological access, and learning resources.

Most previous research has addressed STEM and STEAM separately and has focused primarily on cognitive learning outcomes. Furthermore, the use of digital technology in their implementation has not yet been fully optimized to strike a balance between technological proficiency and the development of students' creativity. Based on the results of the literature review, there remains limited comprehensive integration of STEM and STEAM in digital learning, a lack of innovation that balances technology and creativity, and a need for learning strategies that are more adaptive to developments in the digital age. These gaps indicate that further in-depth research is needed on how the integration of STEM and STEAM can be effectively applied to create innovative learning experiences.

METHODS

This study used a qualitative thematic literature review to synthesize conceptual and empirical evidence on how STEM and STEAM education support innovative learning in the digital era. A qualitative review was selected to identify explanatory themes rather than pool effect sizes across heterogeneous studies. The search and screening procedures are reported to ensure transparency and reproducibility.

Conceptually, the review focuses on the integration and continuity of STEM and STEAM rather than comparison or developmental progression. STEAM is viewed as an extension of STEM through the incorporation of the arts to enhance creativity, design, and innovation. The review therefore synthesizes their shared and extended characteristics in relation to innovative learning and 21st-century skills.

A structured literature search was conducted from 7 to 22 June 2026 using Google Scholar and Scopus. The search used combinations of keywords including *STEM education*, *STEAM education*, *innovative learning*, *digital learning*, *21st-century skills*, *project-based learning*, *problem-based learning*, *creativity*, *critical thinking*, *collaboration*, *communication*, and *problem solving*. The main search strings

combined STEM/STEAM terms with innovative learning, digital learning, project-based/problem-based learning, and 21st-century skills.

Studies were included if they addressed STEM/STEAM education, learning outcomes, student competencies, implementation, challenges, or supporting strategies; were published as scholarly articles, conference proceedings, books, systematic reviews, or meta-analyses; and provided sufficient methodological and bibliographic information. Duplicate, irrelevant, and insufficiently documented sources were excluded.

The selection process involved identification, duplicate removal, title and abstract screening, and full-text assessment. A total of 106 records were initially identified. After screening and eligibility assessment, 45 publications were included in the final synthesis. Data were extracted using a review matrix covering publication characteristics, educational context, STEM/STEAM approach, study design, participants, outcomes, findings, implementation conditions, challenges, and strategies. Because the included studies had heterogeneous designs and outcomes, findings were synthesized thematically rather than statistically. Four themes were identified: (1) Integration of STEM and STEAM in Learning, (2) Outcomes Associated with STEM/STEAM Implementation, (3) Challenges in Implementing STEM & STEAM, and (4) Solutions and Strategies for Developing the Implementation of the STEM and STEAM Curricula.

The methodological quality of empirical studies was appraised using the Mixed Methods Appraisal Tool (MMAT), while systematic reviews and meta-analyses were assessed using appropriate review-quality criteria, including AMSTAR 2 where applicable. Stronger methodological evidence was given greater weight when discussing effectiveness, while qualitative and literature-based findings were interpreted as contextual or explanatory evidence. Numerical findings, including effect sizes, score increases, percentages, and significance values, were checked against their original sources before inclusion in the synthesis.

RESULTS AND DISCUSSION

A. Integration of STEM and STEAM in Learning

STEM is an approach that integrates four fields Science, Technology, Engineering, and Mathematics which, when applied in the learning process, can make knowledge more meaningful. Meanwhile, STEAM is a learning model that combines five disciplines Science, Technology, Engineering, Art, and Mathematics to solve problems (Juniardi, 2023). Both of these approaches focus on integrating various disciplines to create a comprehensive learning experience, breaking down the barriers between science, technology, and the arts, and fostering the development of critical thinking, innovation, and problem-solving skills (Tobondo, 2024). STEAM is an extension of STEM that incorporates the arts into learning activities. The implementation of STEM and STEAM in school education is centered on student-centered learning, featuring inquiry-based, problem-based, and project-based learning; collaboration throughout the learning process; and the application of learning tailored to students' circumstances and needs, followed by evaluation and reflection on the learning process (Nuragnia et al., 2021).

In practice, STEM and STEAM integration not only combines several subjects but is also designed through thematic and contextual approaches that enable students to understand the real-world connections between disciplines. STEM and STEAM learning is grounded in constructivist theory and is closely linked to Problem-Based Learning (PBL) and Project-Based Learning (PBL), which foster the development of Higher Order Thinking Skills (HOTS) and 21st-century skills (Lestari et al., 2026), serves as the primary strategy in its implementation, in which students are encouraged to actively explore, analyze, and create solutions to problems they encounter in daily life (Asyari et al., 2023). For example, students can design simple products that integrate the principles of science, technology, engineering, art, and mathematics. This activity not only enhances conceptual understanding but also fosters critical and creative thinking skills. An example of a STEM & STEAM-based learning project is building a miniature bridge, in which students are asked to design and construct a bridge using simple materials (cardboard, straws, popsicle sticks). This project integrates science (concepts of force, pressure, and

balance), technology (use of design tools), engineering (model design), mathematics (calculating load-bearing capacity), and art (bridge structure design) (Riby, 2024).

In addition, the use digital technology is a key component supporting STEM/STEAM implementation: interactive simulations, educational apps, and other technology-based media help make abstract concepts more concrete (Dulyapit & Winarsih, 2024), and this integration also supports digital literacy alongside critical thinking, creativity, communication, and collaboration (Zuhri et al., 2024). Project-based learning within STEM/STEAM further gives students an authentic experience of planning, implementing, and evaluating solutions to real-world problems, requiring collaboration and time management and building the adaptability associated with 21st-century readiness (Lestari et al., 2026).

B. Outcomes Associated with STEM/STEAM Implementation

The application of STEM and STEAM in learning plays a crucial role in fostering students' creativity and innovation. Through this approach, students do not merely passively receive information; they are also encouraged to generate new ideas and creative solutions to various problems (Lestari et al., 2026). The integration of artistic elements into STEAM provides students with the opportunity to express their ideas more freely and imaginatively, resulting in products that are not only functional but also aesthetically pleasing. Through the design process, students are encouraged to seek unique, alternative solutions to a problem. According to Ulfiani (2026) A STEAM-based learning environment fosters creative thinking, as students are positioned as creators rather than mere consumers of information. STEM and STEAM can create an innovative learning environment and encourage students to become creative and productive individuals.

The application of STEM and STEAM in education is supported not only by theoretical perspectives but also by findings from previous empirical and literature-based studies (Lestari et al., 2026), through a systematic literature review, reported that the integration of STEM and STEAM can support the development of students' creativity, higher-order thinking skills, and 21st-century competencies. Empirical evidence is also provided by Azizah & Angelina (2025). whose quasi-experimental study at SMP Negeri 1 Jombang found that STEM-based learning significantly improved students' creativity and critical thinking skills compared with conventional learning, as indicated by t-test and normalized gain analyses. At a broader level, Chang et al., (2024) conducted an international meta-analysis of 23 studies involving 9,797 students from 70 schools across seven countries and found an overall weighted effect size of 0.38, indicating a small to moderate positive effect of STEM education on students' academic achievement. Similarly, KAZU & YALÇIN (2021) reported a larger effect size ($g = 1.150$) based on 64 effect sizes from 56 quantitative studies, indicating a large positive effect of STEM education on academic achievement. Because these two studies are meta-analyses that aggregate findings across dozens of primary studies and thousands of students, they carry greater methodological weight than the single-classroom and case-study evidence discussed elsewhere in this review, and are therefore treated as the strongest basis for claims about the overall effectiveness of STEM education. Taken together, these findings provide substantial evidence that STEM education can contribute to improved academic achievement, creativity, and higher-order thinking, while literature on STEM/STEAM further highlights its potential to foster innovative and student-centered learning environments.

In addition to fostering creativity, STEM and STEAM also play a role in developing critical thinking and problem-solving skills. During the learning process, students are presented with various real-world problems that require them to analyze, evaluate, and find appropriate solutions. This approach trains students to think systematically and logically when solving problems. Problem-based learning which is frequently used in STEM and STEAM helps students directly understand the connection between theory and practice. As a result, students not only grasp concepts but are also able to apply them in everyday situations. This critical thinking skill is one of the key competencies students must possess to face the challenges of the 21st century. Therefore, the implementation of STEM and STEAM is highly relevant in developing students who are capable of analytical and solution-oriented thinking.

The implementation of STEM and STEAM in learning also plays a role in improving students' collaboration and communication skills. Project-based learning activities are typically conducted in groups, so students are required to work together to complete the assigned tasks. In this process, students learn to share ideas, listen to others' opinions, and convey their own ideas effectively. In

addition, effective communication is essential when presenting project results to teachers and classmates. These collaboration and communication skills are crucial because they reflect the teamwork abilities required in the workplace. Therefore, STEM and STEAM education not only focuses on cognitive aspects but also comprehensively develops students' social skills (Sari & Zulfa, 2024). This makes STEM and STEAM innovative learning approaches that are relevant to the needs of the future.

The implementation of STEM and STEAM in education has various positive impacts on student development cognitively, affectively, and in terms of skills. These impacts can be seen in the following aspects:

1. Impact on Student Learning Outcomes

The implementation of STEM-based learning has been shown to positively influence students' learning outcomes and the development of higher-order skills across different educational levels. A meta-analysis conducted by M. A. Fadillah et al., (2024) found that STEM-based learning was significantly more effective than traditional learning in improving students' learning outcomes, with a large overall effect size ($d = 1.71$, $Z = 7.45$, $p < 0.00001$). The study also reported significant positive effects for both male and female students, although the effect was stronger for male students ($d = 3.15$) than for female students ($d = 1.66$), indicating that the magnitude of the STEM effect varied across gender groups. As a meta-analysis synthesizing multiple primary studies, this finding is treated as stronger evidence than the single-study designs reported below. At the elementary school level, Sejati et al., (2024) found that the STEM learning model significantly improved the learning outcomes of fourth-grade students in IPAS at SDN 1 Guyangan. Using a one-group pretest-posttest design involving 30 students, the study reported an increase in the mean score from 50.13 on the pretest to 80.93 on the posttest. The paired-samples t-test showed a significance value of 0.001, which was lower than the 0.05 significance level, indicating a significant difference between students' pretest and posttest scores. The proportion of students achieving the minimum mastery criterion also increased from 10% in the pretest to 86.67% in the posttest. However, because this study used a one-group pretest-posttest design without a comparison or control group, the observed gains cannot be fully attributed to the STEM intervention alone, and the findings should be interpreted as preliminary rather than strong causal evidence. At the junior high school level, Azizah & Angelina (2025) demonstrated that STEM-based learning contributed positively to students' creativity and critical thinking skills at SMP Negeri 1 Jombang. Their study involved eighth-grade students and found improvements in both creativity and critical thinking in the experimental group. The mean creativity score increased from 45.3 to 78.5, with an N-Gain score of 0.61, while the mean critical thinking score increased from 42.6 to 80.4, with an N-Gain score of 0.66. Furthermore, 85% of students in the experimental group reported greater motivation and interest in STEM-based learning. Taken together, these findings provide empirical evidence that STEM-based learning can support improvements in students' learning outcomes, creativity, critical thinking, and engagement across different educational levels, although the specific effects may vary according to the educational context and the learning outcomes being measured.

2. Impact on Learning Motivation

The implementation of STEM and STEAM significantly increases student learning motivation because this approach makes learning more engaging, relevant, and contextualized to everyday life. Collaborative classroom action research at SDN Sabang, Bandung City, with 28 fourth-grade students showed that STEM learning using the Understanding by Design (UbD) approach increased student learning motivation from 84% in Cycle 1 (Good category) to 98.4% in Cycle 2 (Very Good category) (Nurjanah et al., 2023). As this study was a single-class classroom action research conducted over two cycles without a comparison group, the reported motivational gains reflect within-class change over time rather than generalizable causal evidence. The implementation of STEM on students shows positive results, especially in the motivational aspect, where students are more interested in the lessons because the STEM approach connects the material with their daily lives (Yatim et al., 2024). Literature studies of various empirical articles also show that implementing STEM can increase students' enthusiasm for learning. Furthermore, project-based learning in STEM and STEAM empowers students to feel actively involved in creating solutions, thus building intrinsic motivation to continue independent learning (Rohanah & Amelia, 2026). Therefore, STEM and STEAM not only

improve academic competence but also build the character of students who are confident and enthusiastic.

3. Impact on 21st-Century Skills

The STEAM approach, which integrates science, technology, engineering, art, and mathematics, has been increasingly recognized as an interdisciplinary approach for developing students' 21st-century skills. These skills include critical thinking, creativity, collaboration, communication, problem-solving, digital literacy, and innovation (Rizky, 2025). Through the integration of different disciplines, STEAM provides opportunities for students to apply knowledge, solve problems, develop creative ideas, and collaborate in meaningful learning activities. Rizky (2025) describes STEAM as a holistic and integrated approach that can support the development of multiple 21st-century competencies, including critical thinking, creativity, collaboration, communication, and innovation. However, because the study employed a descriptive qualitative literature-study approach, its findings represent a synthesis of existing literature rather than direct experimental evidence of significant improvement in students' skills.

Empirical evidence from elementary education is provided by Shufa & Adji (2024), who examined the implementation of integrated STEAM learning based on local wisdom and its contribution to the development of the C4: critical thinking, creativity, collaboration, and communication. Using a case study approach, the researchers collected data through classroom observations, interviews with teachers and students, and analysis of learning outcomes before and after the implementation of STEAM learning. Their findings indicated that integrated STEAM learning based on local wisdom supported the development of the C4 among elementary school students, with average scores of more than 3.50 across the four skill categories. These findings suggest that integrating local wisdom into STEAM learning can provide meaningful and contextual learning experiences while supporting the development of essential 21st-century competencies. As a small-scale case study without a comparison group, however, these results are best understood as context-specific evidence rather than a basis for broad generalization.

The development of 21st-century skills can also be supported through STEM-integrated project-based learning. A systematic literature review by Wardana et al., (2024), which analyzed 30 references published between 2019 and 2023, found that STEM-integrated Project-Based Learning (PjBL) positively contributes to students' 21st-century skills, including critical thinking, creativity, collaboration, communication, conceptual understanding, and problem-solving. The review also highlighted the importance of interdisciplinary learning, technology integration, teacher collaboration, and supportive learning environments in implementing STEM-PjBL effectively.

Taken together, these findings indicate that STEM and STEAM can contribute to the development of students' 21st-century skills through interdisciplinary, contextual, collaborative, and project-oriented learning experiences. By engaging students in meaningful problems and integrating knowledge from multiple disciplines, these approaches can provide opportunities for students to develop critical thinking, creativity, collaboration, communication, and problem-solving skills that are increasingly important for future academic, professional, and social contexts.

C. Challenges in Implementing STEM & STEAM

Although they offer many advantages, the implementation of STEM and STEAM in education also faces various challenges, including:

1. Limited Resources and Technology

The implementation of STEM (Science, Technology, Engineering, Mathematics) and STEAM (Science, Technology, Engineering, Arts, Mathematics) requires adequate facilities, such as laboratories, computer equipment, internet access, educational software, and interactive learning materials (Nurfajariyah, A. F., & Kusumawati, 2023). However, many educational institutions still face limitations in terms of facilities and infrastructure, particularly in remote areas and regions where access to technology is not yet widespread (Sarwoedi et al., 2025). Inequality in educational facilities remains a persistent problem in Indonesia, particularly in rural areas. According to 2019 data from the Indonesian Ministry of Education and Culture, approximately 25% of schools in Indonesia are located in remote and outlying areas. Educational facilities in these regions are generally inadequate compared to those available in major cities (R. Fadillah et al., 2025).

These limitations prevent students from having an optimal learning experience when conducting experiments, simulations, or technology-based projects. As a result, the STEM and STEAM learning objectives which aim to develop 21st-century skills such as critical thinking, creativity, collaboration, and problem-solving have not yet been fully achieved.

2. Lack of Teacher Competence

Teachers play a crucial role in the successful implementation of STEM and STEAM. However, there are still educators who lack a sufficient understanding of the concepts, approaches, and learning strategies associated with STEM and STEAM. According to Nuragnia et al., (2021), one of the challenges reported by elementary school teachers in implementing STEAM was inadequate pedagogical support. The study involved 32 elementary school teachers in West Java and Banten, and 68.75% of the respondents (22 teachers) reported inadequate pedagogical support. This challenge included the limited availability of pedagogical models that could guide teachers in delivering STEAM learning in an engaging manner. The study also identified other implementation challenges, including technical constraints (75%), inadequate school facilities (64.06%), and difficulties in accessing STEAM content (59.37%). These findings indicate that teachers' challenges in implementing STEAM extend beyond conceptual understanding and include the availability of practical pedagogical models, technical support, learning facilities, and accessible instructional resources. The importance of teachers' familiarity with STEAM is also highlighted by (Breda et al., 2023), who investigated the perceptions of 62 basic and secondary education teachers in Cape Verde. Only 13 teachers (21%) reported that they had heard about STEAM education. Among these 13 teachers, seven reported learning about STEAM through teacher training courses, including three who specifically referred to GeoGebra training courses, four through online searches, and two through conversations with colleagues. These findings indicate that STEAM education was still relatively unfamiliar among the teachers surveyed and was not yet widely implemented or discussed within their teaching practices or professional development programs.

Taken together, the findings of Nuragnia et al., (2021) and Breda et al., (2023) suggest that strengthening teachers' capacity to implement STEAM requires greater pedagogical support, professional development, and access to appropriate instructional models and resources. Therefore, teacher development programs should not only introduce the theoretical concepts of STEAM but also provide opportunities for teachers to develop practical instructional strategies, design interdisciplinary learning activities, and adapt STEAM approaches to their specific educational contexts.

3. Barriers to Curriculum Integration in the Implementation of STEM and STEAM Education

The implementation of STEM (Science, Technology, Engineering, and Mathematics) and STEAM (Science, Technology, Engineering, Arts, and Mathematics) education requires the integration of various disciplines within the learning process. This approach is designed to help students understand the connections between different fields of study through contextual problem-solving and project-based activities. However, the implementation of STEM and STEAM in schools still faces various challenges, particularly regarding curriculum integration. School curricula are generally still organized around separate subject areas, creating barriers between disciplines. This situation makes it difficult for teachers to connect concepts from various fields of study into a cohesive and meaningful learning experience.

(Madar et al., 2026) revealed that the implementation of STEM still faces obstacles in the form of a mismatch between the traditional education system which focuses on separate academic disciplines and the interdisciplinary nature of STEM learning objectives. Many developing countries still rely on summative assessments based on written exams, which hinder the implementation of skills-based learning (Bahri & Syahrul, 2025). This situation has led to a lack of integration across disciplines and has hindered the optimal implementation of the STEM curriculum. According to (Wang et al., 2011), Teachers' perceptions and understanding of STEM integration tend to be influenced by their respective disciplinary backgrounds, so that instructional implementation often focuses on specific subject areas and does not yet fully reflect interdisciplinary integration. These findings indicate that differences in teachers' perspectives can pose a barrier to designing comprehensive STEM instruction. In line with this, in the study (Margot & Kettler, 2019) It states that the integration of STEM into the curriculum is still viewed as a challenge by some teachers, particularly at the high school level. These challenges relate to the curriculum's limited flexibility, difficulties in integrating STEM into the existing curriculum, and the

presence of rigid learning standards. In addition, the specific nature of subjects at the secondary level makes it difficult for teachers to connect concepts across disciplines.

D. Solutions and Strategies for Developing the Implementation of the STEM and STEAM Curricula

To address the various challenges in implementing STEM and STEAM, appropriate solutions and strategies are needed to ensure that learning proceeds optimally. Solutions and strategies that can be implemented include:

1. Curriculum Alignment

Curriculum alignment is the process of ensuring consistency among learning objectives, competency outcomes, instructional content, learning strategies, and assessments so that all components of the curriculum support the optimal achievement of learning outcomes. In the context of STEM (Science, Technology, Engineering, and Mathematics) and STEAM (Science, Technology, Engineering, Arts, and Mathematics) education, curriculum alignment is a fundamental aspect because these approaches emphasize interdisciplinary integration to address increasingly complex global challenges. The development of STEM and STEAM curricula must be aligned with national education priorities, the Sustainable Development Goals (SDGs), and 21st-century competencies (Taguma & Barrera, 2019). This alignment can be achieved by integrating contextual issues such as climate change, health, digital transformation, and technological innovation into the learning outcomes.

A strategy for aligning STEM and STEAM curricula can be implemented by developing a cross-subject competency integration map so that the connections between learning outcomes can be systematically identified (Kelley & Knowles, 2016). The development of project-based teaching modules integrated with the Sustainable Development Goals (SDGs) is an effective strategy for enhancing the relevance of STEM and STEAM education. Project-based learning enables students to explore real-world problems and develop problem-solving, collaboration, and critical thinking skills within the context of sustainability. In addition, learning outcome indicators should be designed not only to measure conceptual mastery but also 21st-century skills, such as critical thinking, creativity, communication, collaboration, and digital literacy.

2. Pedagogical Innovation

The implementation of STEM and STEAM requires a paradigm shift from conventional learning toward inquiry-based, problem-solving, and project-based learning. One pedagogical innovation strategy that can be applied is the use of Project-Based Learning (PjBL), Problem-Based Learning (PBL), and Inquiry-Based Learning models. These three models provide students with the opportunity to actively engage in the learning process through in-depth investigation of authentic problems. Research findings (Gultom & Nasution, 2026) shows that the consistent implementation of STEM-integrated PjBL has a positive impact on the development of 21st-century skills, particularly critical thinking, creativity, communication, collaboration, and problem-solving. The results of the study (Dianti et al., 2023) states that the implementation of Project-Based Learning (PjBL) has a significant impact on improving students' science literacy skills. Thus, PjBL can serve as an effective alternative learning strategy to optimize the quality of learning.

3. Strengthening Teacher Competencies

Teacher competencies are a key factor in the successful implementation of STEM and STEAM. Competencies are a set of knowledge, skills, and task-related behaviors that teachers must possess, internalize, master, and demonstrate in carrying out their professional duties in the classroom a process known as teaching (Hafsah M. Nur & Nurul Fatonah, 2023). Educators must possess the competencies needed to serve as facilitators of student learning; therefore, ongoing professional development is necessary to enhance the quality of their competencies. Research (Nuragnia et al., 2021) revealed that one development strategy that can be implemented to improve teacher competence is through STEAM training. This study shows that teachers who have participated in the training experienced significant benefits, particularly in enhancing their understanding of STEAM learning methods and models that can be applied in the classroom. The training helped teachers understand the characteristics of project-based, inquiry-based, and problem-solving learning, which are hallmarks of the STEAM approach.

4. Resource and Infrastructure Support

The availability of adequate facilities and infrastructure is an essential prerequisite for supporting STEM and STEAM education. The availability of adequate resources and infrastructure is one of the key prerequisites for the successful implementation of STEM (Science, Technology, Engineering, and Mathematics) and STEAM (Science, Technology, Engineering, Arts, and Mathematics) education. The characteristics of STEM and STEAM education which emphasize project-based activities, experiments, engineering design, and the use of digital technology require adequate facilities and infrastructure to ensure that the learning process can take place optimally.

Learning facilities that support the implementation of STEM and STEAM include the availability of laboratories, flexible classrooms, information and communication technology devices, internet access, digital teaching materials, and tools and materials for experiments and projects. The availability of these resources enables students to explore, collaborate, and solve problems firsthand through authentic learning experiences. Limited facilities and resources remain one of the main challenges schools face in implementing integrated STEM education. The availability of teaching aids, learning media, and supporting facilities such as internet connectivity remains an obstacle for some schools in implementing STEM education (Mawaddah et al., 2025). As a result, teachers often face difficulties in implementing project-based learning due to a lack of access to equipment, hands-on materials, and supporting technology.

The implementation of STEAM does not always depend on the availability of expensive or high-tech facilities and infrastructure. Although well-equipped facilities can enhance the quality of learning, the STEAM approach is inherently flexible and can be adapted to the conditions and resources available at the school. The application of STEAM allows teachers to design contextual learning experiences by utilizing various resources available in the surrounding environment. For example, STEAM activities can be carried out through simple projects, such as model-making, conducting simple experiments, or using free digital applications available online without requiring specialized, high-cost equipment. In this regard, teachers' creativity plays a crucial role in optimizing available resources. Teachers can use materials that are easily found in the surrounding environment or recycled items as media for experiments, prototyping, or art projects relevant to STEAM concepts (Anggrella et al., 2024).

CONCLUSION

STEM/STEAM-based learning is a relevant and effective approach to addressing the demands of 21st-century education, particularly in developing critical, creative, collaborative, and communicative thinking skills in students. The application of STEM focuses not only on conceptual mastery but also on the ability to solve real-world problems through the integration of various disciplines. The use of learning designs such as Understanding by Design (UbD) strengthens STEM implementation by helping teachers design learning that is focused on the ultimate goal (learning outcomes) and provides meaningful learning experiences. Furthermore, the integration of digital technology and innovative approaches is a crucial factor in improving the quality of learning.

However, STEM implementation still faces various challenges, such as limited teacher understanding, inadequate infrastructure, and limited educational system readiness. Therefore, support in the form of teacher training, curriculum development, and supportive educational policies is needed. Overall, STEM/STEAM learning has significant potential to improve the quality of education and prepare students for current developments, provided it is implemented in a planned, systematic manner, and supported by various parties.

These conclusions, however, should be read in light of the varying methodological strength of the evidence reviewed. Meta-analyses aggregating results across dozens of primary studies and thousands of participants (e.g., Chang et al., 2024; Fadillah et al., 2024; KAZU & YALÇIN, 2021) provide the most robust support for the effectiveness of STEM/STEAM education, whereas quasi-experimental studies with comparison groups offer moderate support, and single-classroom action research, one-group pretest-posttest designs, and case studies provide preliminary, context-specific evidence that cannot alone establish generalizable causal effects. The conclusions above therefore give greater weight to the meta-analytic and quasi-experimental evidence, while findings from smaller-scale or non-controlled

studies are treated as illustrative of implementation contexts rather than proof of generalized effectiveness.

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