Effectiveness of STEAM Education in Enhancing 21st Century Skills: A Systematic Review

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Abstract

Traditional subject-focused instruction often fails to equip students with the interdisciplinary competencies needed in today's innovation-driven world. STEAM education has emerged as a promising model for strengthening 21st-century skills. This review systematically examined recent empirical studies that compared STEAM interventions with traditional methods. Sources were drawn from diverse contexts, including Asia, Europe, and North America, covering a range of educational levels, including elementary, secondary, and inclusive classrooms. Evidence suggests that project-based learning and the integration of technology within STEAM consistently enhance collaboration, communication, and problem-solving. Creativity and critical thinking showed mixed outcomes—technology-based strategies, such as augmented reality and coding, improved engagement and computational thinking. Inclusive classrooms demonstrated benefits for both neurotypical and autistic learners. STEAM approaches demonstrate clear advantages over conventional teaching; however, their generalizability remains limited by the small-scale and context-specific nature of existing studies. Larger, long-term investigations are needed to confirm sustained impacts.

Keywords: STEAM Education, 21st-Century Skills, Project-Based Learning, Technology Integration, Inclusive Classrooms.

Introduction

The rapid evolution of knowledge economies and technology-driven societies has heightened the demand for educational models that cultivate 21st-century skills such as collaboration, creativity, problem-solving, and critical thinking. Traditional subject-specific instruction, while effective in conveying disciplinary knowledge, often falls short in fostering the interdisciplinary and applied competencies required in contemporary learning and work environments. In response, STEAM (Science, Technology, Engineering, Arts, and Mathematics) education has emerged as a promising framework for integrating multiple domains through creative and inquiry-driven practices.

A growing body of research suggests that STEAM interventions, particularly those incorporating project-based learning and emerging technologies, can offer measurable advantages over conventional approaches. For example, studies exploring Asian contexts provide notable insights. Yang and Cheng (2023) found medium effect sizes in communication, collaboration, and problem-solving among elementary students in Taiwan. In contrast, Zaqiah et al. (2024) reported significant improvements in cooperation between Indonesian junior high

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students, although changes in creativity, communication, and critical thinking were less consistent. In Thailand, Chansaengsee (2024) documented broad and statistically significant gains across eight skills, including literacy, numeracy, problem-solving, and collaboration, within an inclusive classroom setting. Moving to European settings, additional evidence highlights varied benefits. In addition to these results, Jesionkowska et al. (2020) reported that STEAM activities led to higher engagement and promoted computational thinking through the use of technology (augmented reality and coding workshops), and research in chemistry education demonstrated positive effects on problem-solving and creative use of knowledge (Ridwan et al., 2021; Hadinugrahaningsih et al., 2017). Likewise, Kurt and Benzer (2020) found that STEM activities incorporated into middle school science classes in Turkey significantly enhanced academic performance, STEM-oriented attitudes, and problem-solving abilities compared with traditional teaching methods.

Collectively, these studies indicate that STEAM approaches, especially those emphasizing project-based learning and technology, tend to strengthen collaboration, problem-solving, and selected communication skills; however, the effects on creativity and critical thinking are more variable. At the same time, contextual factors such as intervention duration, inclusivity, and the extent of technology integration shape the breadth and sustainability of skill development.

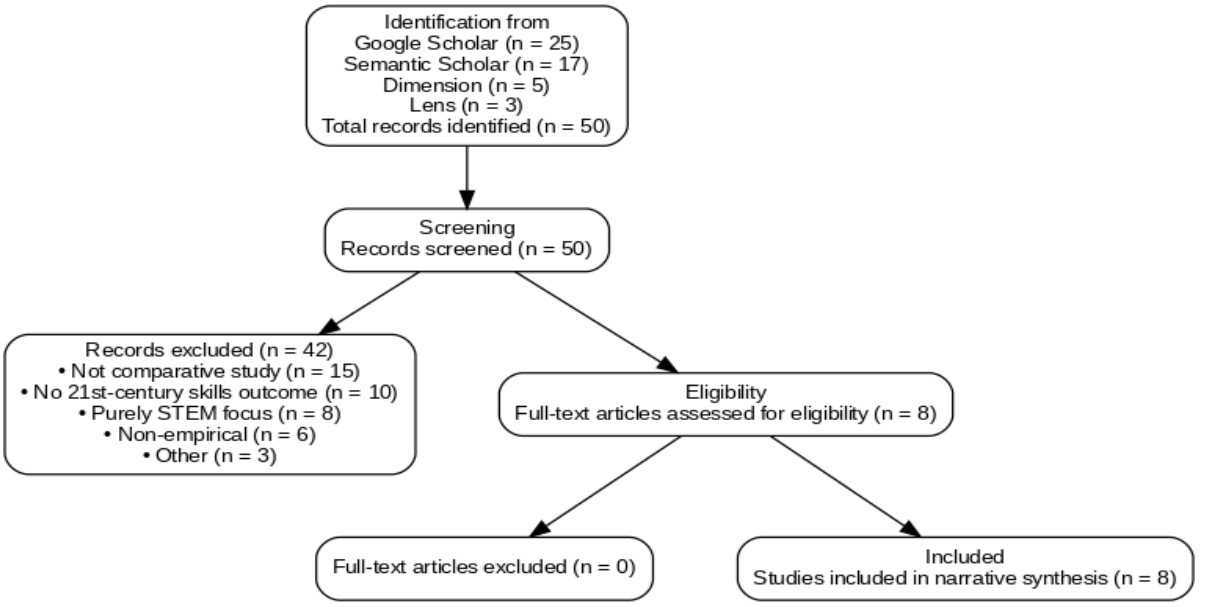
Despite these encouraging findings, the evidence base is fragmented, with many studies conducted in small, context-specific settings that limit broader generalizability. There is also ongoing debate regarding which pedagogical methods within STEAM are most effective in strengthening distinct skill domains. Addressing these gaps requires a systematic review of recent empirical work that directly compares STEAM approaches with traditional methods in enhancing students' 21st-century skills.

This review responds to that need by synthesizing studies conducted across multiple countries, educational levels, and implementation strategies. The findings, summarized in Table 2 and analyzed in the Results section, provide a comprehensive view of how STEAM interventions influence various 21st-century skills and highlight the contextual factors that condition their impact.

Methodology

Search Strategy

Figure 1: PRISMA-like Flowchart of the Study Selection Process.



To address the research question "how do STEAM education interventions compare to traditional teaching methods in enhancing students' 21st-century skills across various educational settings?" we conducted a structured literature search using the Google Scholar, Semantic Scholar, Dimension and Lens databases. The search query combined terms related to STEAM education, traditional teaching methods, and 21st-century skills. Specifically, the following search string was employed across all databases: ("STEAM education" OR "STEM education" OR "Science Technology Engineering Arts Mathematics") AND ("21st century skills" OR "twenty-first century skills" OR "collaboration" OR "communication" OR "critical thinking" OR "creativity" OR "problem-solving") AND ("traditional teaching" OR "conventional teaching" OR "traditional instruction" OR "conventional instruction").From this process, the 50 most relevant papers were initially retrieved.

Screening Process

Following the initial search, each retrieved paper was systematically screened according to a predefined set of inclusion and exclusion criteria. The detailed flow of this selection process, from identification to final inclusion, is presented in Figure 1. A study was included if it satisfied all of the following:

1. *STEAM Integration:* The intervention integrated at least three of the five STEAM domains (Science, Technology, Engineering, Arts, Mathematics) in an interdisciplinary manner.
2. *Educational Population:* The participants were enrolled in formal educational settings (K-12, undergraduate, or graduate).
3. *21st-Century Skills Outcomes:* At least one skill such as critical thinking, creativity, collaboration, communication, problem-solving, digital literacy, or innovation was assessed.
4. *Comparative Study Design:* The study compared STEAM interventions with traditional teaching methods using experimental, quasi-experimental, or comparative designs.
5. *Clear Intervention Description:* The STEAM intervention was explicitly described and distinguishable from traditional approaches.
6. *Arts Integration:* Arts were integrated into the intervention rather than focusing solely on STEM.
7. *Beyond Academic Achievement:* Outcomes extended beyond subject-specific performance to include skills, dispositions, or competencies aligned with 21st-century learning.
8. *Empirical Research:* Only empirical research studies were included; conference abstracts, editorials, and opinion pieces were excluded.

Screening decisions were made holistically, considering the overall relevance of each paper to the inclusion criteria.

Data Extraction

For each included study, we extracted the following information:

- *Study Design Type:* Categorized as experimental (randomized controlled trial), quasi-experimental, comparative study, single-group intervention, or mixed methods, based on the primary methodological approach.
- *Research Setting and Context:* Level of education, school type (public/private), geographic location, and subject area in which the intervention was implemented.
- *STEAM Intervention Details:* Components of STEAM integration, pedagogical methods (e.g., project-based, inquiry-based), duration, and learning activities, recorded verbatim where possible.
- *Comparison/Control Condition:* Type and nature of control or comparison group, including traditional teaching or alternative approaches.

- *21st-Century Skills Measured:* Specific skills assessed, measurement tools used, and operationalization strategies.
- *Key Findings:* Quantitative and qualitative outcomes related to 21st-century skills development, including statistical results and qualitative themes.
- *Participant Characteristics:* Sample size, grade level, age range, gender distribution, and other demographic or contextual information.

Data extraction was supported by a large language model (LLM), which was provided with explicit extraction instructions for each column. All outputs were checked for accuracy and consistency with the full texts.

Data Synthesis

Extracted information was organized into summary tables (see Table 1) to allow structured comparison of study characteristics, intervention methods, measured outcomes, and reported findings. Narrative synthesis was then conducted to identify common patterns, divergences, and gaps across the included studies.

Results

Educational Level and Setting

The included studies represented a diverse range of educational contexts (see Table 2). Three studies were situated in elementary schools, while five focused on secondary-level students, including junior high populations. One study was conducted in an inclusive classroom environment, highlighting the applicability of STEAM approaches beyond conventional schooling structures. Geographically, the research was spread across several regions: Taiwan, Canada, the United Kingdom, Indonesia, Thailand, and Greece each contributed one study, whereas two studies did not specify their location in the abstract or full text where available. In terms of school type, four studies were carried out in public schools, three in private schools, and one in a nonprofit educational setting.

STEAM Implementation Methods

Across the included studies, project-based learning was the most frequently used pedagogical method, appearing in five studies. Two interventions were explicitly chemistry-focused, integrating STEAM within subject-specific contexts. Other implementation strategies were varied and often combined multiple approaches. These included makerspaces, inquiry-based or project-based formats, augmented reality-based learning, active learning, coding workshops, group work, exhibitions, design thinking, multimodal instruction, interdisciplinary learning, and student-driven projects. The tendency to merge several of these methods within a single intervention underscores the flexibility and multidimensional nature of STEAM education.

Measured 21st-Century Skills

The reviewed studies assessed a wide array of 21st-century skills (Table 2). Collaboration and problem-solving were the most frequently examined, each reported in five studies. Communication and critical thinking were measured in four studies, while creativity was assessed in three. A smaller set of studies investigated less frequently reported competencies, including innovation, perseverance, adaptability, coding, computational thinking, teamwork, project management, argumentation, self-direction, motivation, learning strategies, intrinsic goal orientation, help seeking, English literacy, numeracy, scientific literacy, and social or cultural awareness. Each of these was measured in only one study. Notably, one study (Hadinugrahaningsih et al., 2017) did not explicitly mention any 21st-century skills in the abstract, which limited comparability.

Reported Effects on 21st-Century Skills

Evidence from the subset of studies with available statistical reporting suggests generally positive outcomes of STEAM interventions compared with traditional teaching approaches (Table 2). For example, Yang and Cheng (2023) reported medium effect sizes, with students in the experimental group showing greater improvements in communication, collaboration, and problem-solving than those in the control group. Similarly, Zaqiah et al. (2024) found notable gains in collaboration, where the proportion of students at the lowest level decreased by 52%, although effects on critical thinking and communication were not significant. The Thai study (Chansaengsee, 2024) reported significant improvements across all eight assessed skills ($p \leq .01$), including English literacy, numeracy, scientific literacy, problem-solving, creativity, communication, collaboration, and social/cultural awareness. In contrast, the study by Kurt & Benzer (2020) demonstrated significant improvements in motivation and learning strategies, but no significant change in intrinsic goal orientation, critical thinking, or help-seeking behaviors.

Study Design

The methodological approaches also varied across the studies. Four were conducted using quasi-experimental designs, while three employed mixed-methods approaches. Two studies were classified as single-group interventions (Jesionkowska et al., 2020; Ridwan et al., 2021) and two were primarily case studies (Bertrand and Namukasa, 2020; Jesionkowska et al., 2020). Two were single-group intervention studies, and another two were described as case studies. In addition, two studies used qualitative intervention approaches, and one adopted a pre–post design without a control group. This distribution not only highlights the prevalence of quasi-experimental and mixed-methods designs but also shows the relative scarcity of randomized controlled trials in the field.

Synthesis of Findings

The results collectively reveal several coherent patterns. Project-based learning emerged as the dominant vehicle for STEAM integration, particularly at the elementary and secondary levels, suggesting that active, hands-on approaches are considered most effective for cultivating 21st-century skills. The skills that were most commonly measured and demonstrated significant improvements were collaboration, problem-solving, communication, and critical thinking due to their role in research and practice. Meanwhile, the competencies related to digital literacy, social awareness, or adaptability received less focus, suggesting avenues for future research. The prevalence of quasi-experimental and mixed-method designs implies that although the field is producing helpful comparative knowledge, additional rigorous experimental studies are needed to establish causal relationships. In general, the evidence base demonstrates the potential of STEAM strategies to improve a wide range of 21st-century skills, while highlighting methodological and topical gaps.

Table 1: Characteristics of Included Studies

Study	Education Level/Setting	STEAM Implemented Methods	21st Century Skills Measured	Study Design	Full Text Retrieved
Yang and Cheng, 2023	Elementary (Grades 4–6), Taiwan	STEAM project-based learning with emerging technologies	Communication, collaboration, problem-solving	Quasi-experimental	Yes
Bertrand and Namukasa, 2020	Secondary (Grades 2, 5, 7, 8,	STEAM programs, makerspaces,	Critical thinking, problem-solving,	Mixed methods	Yes

	9–11), Ontario, Canada; nonprofit and public schools	inquiry/project-based learning	collaboration, communication, creativity, innovation, perseverance, adaptability	(primarily qualitative case study)	
Jesionkowska et al., 2020	Secondary (Year 10, 11, 6th Form), Oxford, UK	Augmented reality-based STEAM, active learning, coding workshops	Coding, computational thinking, teamwork, problem-solving, project management	Single group intervention (case study)	Yes
Zaqiah et al., 2024	Islamic junior high (secondary), West Java, Indonesia; public and private	STEAM project-based learning, 3 sessions, group work, exhibitions	Critical thinking, communication, collaboration, creativity	Mixed methods (quasi-experimental)	Yes
Chansaengsee, 2024	Grade 6, inclusive classroom, Thailand	STEAM project-based learning, design thinking, multimodal, 2 semesters	English literacy, numeracy, scientific literacy, problem-solving, creativity, communication, collaboration, social/cultural awareness	Quasi-experimental (pre-post, no control)	Yes
Ridwan et al., 2021	Secondary (Year 10, 11), public/private, unspecified location	STEAM in chemistry, modified project-based learning, student projects	Critical/creative thinking, problem-solving, collaboration, argumentation, self-direction	Single group intervention (qualitative)	Yes
Kurt, M., & Benzer, S. (2020)	6th grade elementary, Chalandri, Greece	STEAM for atherosclerosis, interdisciplinary	Motivation, learning strategies, intrinsic goal orientation, critical thinking, help seeking	Quasi-experimental	Yes
Hadinugrahaningsih et al., 2017	Secondary (Year 10, 11), public/private, unspecified location	STEAM in chemistry, modified project-based learning, student projects	Not specified in abstract	Mixed methods (qualitative intervention)	Yes

Note: STEAM = Science, Technology, Engineering, Arts, and Mathematics.

Table 2: Effects of STEAM Education Interventions Compared to Traditional Methods

Study	Study Context	Specific Skills	Effect Size/Statistical Significance	Sample Size
Yang and Cheng (2023)	Elementary, Taiwan, 7 schools	Communication, collaboration, problem-solving	Medium effect sizes; experimental group reported greater improvement than control group	343 (173 experimental, 170 control)
Zaqiah et al. (2024)	Islamic junior high, Indonesia, 2 schools	Collaboration, creativity, critical thinking, communication	Collaboration: significant improvement (52% reduction in lowest level, 17% at Level 3); creativity: slight improvement;	30 (15 per school)

			critical thinking and communication: no significant change	
Chansaengsee, (2024)	Grade 6, inclusive, Thailand	8 skills (English literacy, numeracy, scientific literacy, problem-solving, creativity, communication, collaboration, social/cultural awareness)	All skills: significant pre-post improvement ($p \leq .01$); e.g., English literacy 54.69→69.81, numeracy 60.69→76.81, scientific literacy 59.82→77.50, problem-solving 3.46→4.10, creativity 3.26→3.89, communication 3.84→4.23, collaboration 3.80→4.00, social/cultural awareness 3.78→4.28	19 (16 typical, 3 autistic)
Kurt and Benzer (2020)	6th grade, Greece	Motivation, learning strategies, intrinsic goal orientation, critical thinking, help seeking	Significant increase in motivation and learning strategies; no significant change for intrinsic goal orientation, critical thinking, and help seeking	26 Students (13 controlled Group and 13 Experimental Group)

Discussion

The implications of the results of this review are that STEAM education holds substantial potential for improving 21st-century skills compared with traditional methods. Students who were exposed to STEAM in various settings, including elementary schools in Taiwan and inclusive classrooms in Thailand, consistently demonstrated better results in cooperation, communication, and motivation (see Table 2). These outcomes are consistent with evidence indicating the interdisciplinary, practical nature of STEAM develops competencies at the core of lifelong learning and employability (Kessler et al., 2024; Wahyudi et al., 2024).

The aspect that remained remarkably consistent throughout the studies was project-based learning, often accompanied by complementary strategies, including the use of coding workshops, augmented reality, and interdisciplinary design thinking. The focus on investigating and real problem-solving could be the reason why collaborative skills and problem-solving skills demonstrated the steadiest and most consistent improvements. This finding aligns with recent evidence suggesting that STEAM-based project-based learning is particularly effective in developing creativity and teamwork compared to teacher-focused instruction (Wahyudi et al., 2024).

Meanwhile, the influence of STEAM on higher-order cognitive abilities appears less uniform. Some studies reported an improvement in critical thinking or creativity, while others reported minimal or no improvement. These trends can also be observed in recent meta-analyses, which indicate that the benefits of STEAM in creativity are subject-area specific, duration-dependent, and teacher-expertise dependent (Muneer et al., 2025; Chang et al., 2025). Similarly, studies of sustainable STEAM also highlight substantial outcomes related to critical thinking dispositions in students and mathematics performance; however, they do not consistently generalize these benefits to other settings (Küçülik et al., 2023). The disproportionate outcomes of our review reflect these larger findings, in that, unless appropriate scaffolding is provided, skills such as creativity and critical thinking may not be developed to the same extent as collaboration or motivation.

Another critical aspect is inclusivity. The Thai paper reviewed showed that STEAM has the potential to serve both neurotypical and autistic students, which emphasizes its ability to accommodate diverse learners. This aligns with the general literature, which indicates that STEAM interventions, especially those involving design thinking and interdisciplinary projects, may widen access and foster sustainable development objectives (Ilham Rosyida & Kurtuluş, 2024). Nonetheless, such evidence remains limited, and more efforts are required to investigate the ways of adapting STEAM to various learners and cultural backgrounds.

Overall, the field remains in a developmental stage. The use of quasi-experimental and mixed-method studies is helpful, but does not provide the necessary rigor to make a solid causal relationship. Small sample sizes in some studies further limit generalizability. It is essential to note that some included studies did not provide full texts, which limited our ability to extract comprehensive quantitative data for all studies initially identified in the screening phase. Consequently, this led to a more focused statistical synthesis of the four studies presented in Table 2. Recent reviews have underscored this methodological gap, calling for larger trials and more systematic teacher preparation programs to ensure fidelity of implementation (Kessler et al., 2024). Without such efforts, the evidence base for STEAM risks will remain fragmented.

Taken together, the reviewed studies and the broader literature converge on the view that STEAM education represents a meaningful departure from traditional instruction, one that fosters not only disciplinary understanding but also the collaborative and creative capacities essential for navigating a complex world. Its most consistent contributions are in motivating learners and enhancing their ability to work together. At the same time, its effects on creativity and critical thinking remain variable and dependent on program design. Future research should prioritize rigorous, large-scale designs that examine not just whether STEAM "works," but under what conditions and for whom it produces the most significant benefits.

Conclusion

The evidence reviewed in this study highlights the increasing importance of STEAM education as a catalyst for 21st-century skill development. Across various contexts, from elementary classrooms in Taiwan to inclusive settings in Thailand, STEAM interventions consistently demonstrate measurable gains in communication, collaboration, problem-solving, and creativity. Concurrently, the results reveal that these advantages are not equal; skills such as critical thinking and intrinsic motivation may require more specific approaches to achieve significant improvement.

Notably, STEAM education does not simply serve to improve academic achievement but to transform the learning process. It enhances learners' capabilities to excel in knowledge- and innovation-driven economies by developing curiosity, flexibility, and social awareness. To educators and policymakers, it is now time to shift their focus from small-scale studies to developing large-scale curriculum integration of STEAM approaches. This will involve teacher preparation, reassessment, and inclusivity, ensuring that a variety of learners, including students with special educational needs, can be accommodated.

Finally, STEAM does not prescribe specific methods or curricula; rather, it is a way of developing learners who can be critical, collaborative, and creative about complex problems, fostering resilience and perseverance. With the world education system facing rapid technological and social transformations, the need to incorporate the principles of STEAM at all levels of education has become imperative to equip the future generation with the skills to become future problem-solvers and innovators.

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