The Effectiveness of Integrated STEM Approaches on Secondary School Students' Critical Thinking: A Systematic Literature Review (2019–2025)

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DOI: https://dx.doi.org/10.47772/IJRISS.2025.927000011

Received: 12 November 2025; Accepted: 18 November 2025; Published: 26 November 2025

ABSTRACT

This Systematic Literature Review (SLR) synthesizes empirical evidence published between 2019 and 2025 on the effectiveness of integrated Science, Technology, Engineering, and Mathematics (STEM) approaches in enhancing secondary school students' Critical Thinking (CT) skills. Following the PRISMA 2020 guidelines, a total of 201 records were identified (48 from Scopus and 153 from Google Scholar), from which 17 empirical studies met the inclusion criteria. The findings demonstrate that integrated STEM (iSTEM) interventions generally have a positive impact on students' CT, particularly in developing analytical reasoning, problem-solving, and collaborative inquiry. Effective approaches included Project-Based Learning (PjBL), Problem-Based Learning (PBL), and Design-Based or Robotics-Integrated Inquiry. However, persistent challenges remain concerning teacher preparedness, curriculum alignment, and the valid assessment of CT. Overall, iSTEM education demonstrates strong potential to cultivate CT among secondary school learners. Nevertheless, future research should include more longitudinal designs, standardized assessment tools, and targeted professional development to strengthen implementation and sustainability.

Keywords: Integrated STEM, Critical Thinking, Secondary School, PRISMA, Systematic Literature Review

INTRODUCTION

Critical Thinking (CT) is increasingly recognized as a cornerstone competency across all levels of education (García-Carmona, 2023; Loyens et al., 2023b) and within contemporary professional sectors (Bezanilla & Galindo-Domínguez, 2021). Mastery of CT is fundamental for both personal growth and civic engagement, particularly in an era characterized by rapid technological advancement and shifting global labor demands (Vincent-Lancrin, 2023)

The importance of CT is further underscored by the growing need for individuals who can make informed, ethical, and empathetic judgments to counteract biased or irrational decision-making (Mascarenhas et al., 2023b). In contrast, a deficiency in CT can impede one's ability to recognize and evaluate potential consequences in personal, social, and professional contexts (Mascarenhas et al., 2023a). Correspondingly, recent data from the World Economic Forum (2023) project a 45% to 75% increase in demand for professionals in emerging fields such as Big Data analytics, Artificial Intelligence (AI), and Cloud Computing, all of which rely heavily on CT and problem-solving skills (Loyens et al., 2023; World Economic Forum, 2023).

Within this landscape, secondary school marks a critical stage in cognitive development, aligning with Piaget's formal operational stage (1950), where learners begin to reason beyond concrete experiences and engage in abstract, logical thinking. According to Piaget (1950), this period marks the emergence of formal operational thought, where learners begin to reason logically beyond tangible experiences and engage in hypotheticaldeductive thinking. Empirical evidence supports this transition, with Bitzenbauer et al. (2023) revealing that students' understanding becomes increasingly abstract and systematically organized as they progress through secondary education. Similarly, Abrami et al. (2015) highlighted the significance of fostering

CT during this stage, as students remain highly receptive to instructional strategies that promote higher-order reasoning.

Building on this developmental foundation, integrated STEM (iSTEM) education, which meaningfully connects Science, Technology, Engineering, and Mathematics (STEM), serves as an effective pedagogical framework for nurturing CT (Yaki, 2022; Asrizal et al., 2022; Hebebci & Usta, 2022). By engaging students in authentic problem-solving, inquiry, and collaboration, iSTEM has been demonstrated to foster creativity, analytical reasoning, and reflective inquiry, key components of CT (Ha et al., 2023; Rosidin et al., 2019).

Although research on iSTEM has expanded in recent years, evidence regarding its impact on the development of CT among secondary school students remains fragmented. Previous reviews (e.g., Becker & Park, 2011; Thomas & Larwin, 2023) have largely examined general learning outcomes or teacher perspectives, leaving a gap in understanding how iSTEM influences CT among secondary learners.

To address this gap, this Systematic Literature Review (SLR) synthesizes empirical studies published between 2019 and 2025 to examine how iSTEM approaches influence the development of CT among secondary school students. The review aims to identify emerging trends, effective instructional strategies, and remaining research gaps in the current literature.

1. **RQ1:** What are the characteristics and trends of studies investigating iSTEM and CT?
2. **RQ2:** What teaching approaches and strategies in iSTEM are reported to develop CT?
3. **RQ3:** To what extent is iSTEM shown to be effective in enhancing students' CT?
4. **RQ4:** What gaps and recommendations emerge from the existing literature?

METHODOLOGY

Review Protocol

The review followed the PRISMA 2020 guidelines for reporting systematic reviews, and the flow of study selection is presented in the PRISMA flow diagram for systematic reviews, ensuring transparency and replicability (Page et al., 2021).

Search Strategy

A systematic search was conducted in two major databases: Scopus and Google Scholar, covering the years 2019 to 2025. Search terms included combinations of *integrated STEM, critical thinking, middle school, secondary school,* and *effectiveness*. The following search string was established: ("integrated STEM" OR "iSTEM" OR "STEM integration") AND ("critical thinking" OR "higher order thinking skills" OR "HOTS").

Inclusion and Exclusion Criteria

To ensure that only relevant and high-quality studies were included, a set of inclusion and exclusion criteria was established prior to screening. The inclusion criteria focused on selecting empirical, peer-reviewed studies that implemented iSTEM interventions and measured outcomes related to CT or Higher-Order Thinking Skills (HOTS) among school-aged learners. At the same time, exclusion criteria were applied to filter out studies that were conceptual, theoretical, focused on teacher populations, or did not report CT outcomes. The criteria used for study selection are summarised in Table 1.

Table 1: Inclusion and exclusion criteria

Inclusion	Exclusion
Empirical, peer-reviewed studies	Non-empirical papers (conceptual, theoretical, policy briefs)
Focus on iSTEM	Studies not implementing iSTEM
Outcomes include critical thinking or HOTS	Studies focusing only on motivation, interest, or academic achievement

Participants are secondary school students (Grades 6–9)	Studies involving pre-service teachers, in-service training, university students, or primary school students
Published 2019–2025 in English	Articles outside the date range or not in English
Accessible (open-access or through institutional subscription)	Review articles (systematic reviews, metaanalyses); articles with no full-text access
	Developmental research describing only the design phase without implementation or outcome data

Search Strategy

Scopus and Google Scholar were selected as the primary databases due to their comprehensive coverage of peer-reviewed research in STEM education. The search was conducted between 2019 and 2025, limited to studies published in English.

The following Boolean search string was applied in both databases:

("integrated STEM" OR "iSTEM" OR "STEM integration") AND ("critical thinking" OR "higher order thinking skills" OR "HOTS").

FINDINGS

Study Selection

A total of 201 records were retrieved from Scopus (n = 48) and Google Scholar (n = 153). After removing 160 duplicate and irrelevant records, 40 studies remained for title and abstract screening. Subsequently, 16 were excluded for not meeting the inclusion criteria, leaving 24 for full-text review. During eligibility assessment, seven were excluded: one non-empirical, four involving non-secondary participants, and two with mixed samples including undergraduates, resulting in 17 empirical studies included in the final synthesis.

The PRISMA flow diagram (Figure 1) illustrates the step-by-step process of identification, screening, eligibility assessment, and final inclusion of studies. This process ensured that only empirical studies directly addressing the effectiveness of iSTEM on middle school students' CT were synthesized.

Figure 1: PRISMA Flow Diagram of Study Selection Process

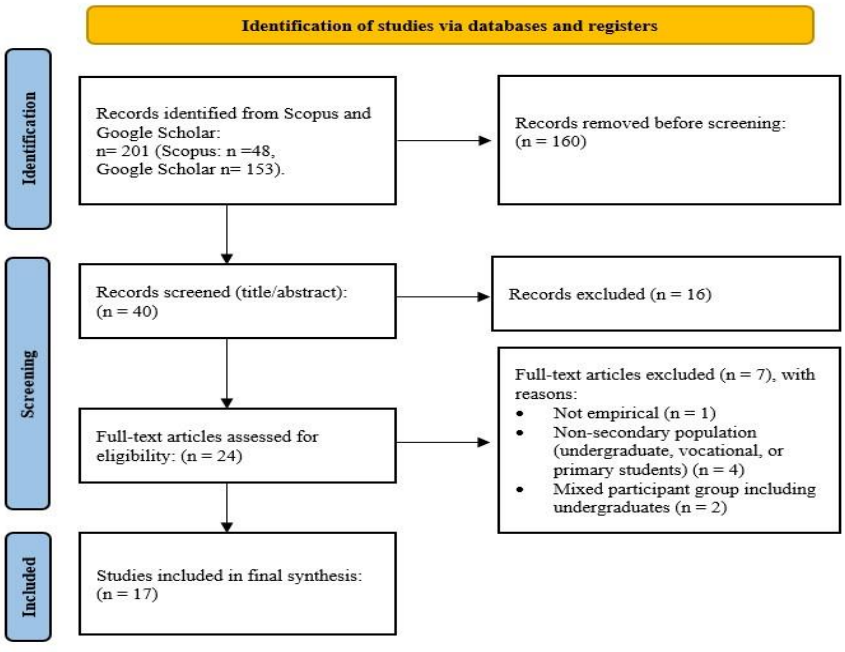

Figure 1: PRISMA Flow Diagram of the study selection process *S*

Study Characteristics

Table 2 presents an overview of the 17 studies included in this review, summarizing publication year, country, participants, research design, teaching approaches, and key findings related to CT outcomes.

Table 2: Overview of the 17 studies included in the review.

Author(s), Year	Country	Intervention/Approach	Research Design	Sample (Secondary)	CT/HOTS Aspects	Method/Instrument Used	Key Findings	Source
Thomason & Hsu (2025)	USA	iSTEM curriculum	Mixedmethod	Middle school	Design thinking dispositions, CT	Pre-post survey; interviews	No significant statistical difference; perceived gains in problem solving & collaboration	Scopus
Yaki (2022)	Nigeria	STEM Genetics Module	Quasiexperimental	112, middle school biology	Inference, assumption, deduction, interpretation, evaluation	Critical Thinking Skill Test	Large effect size (d = 1.56), significant CT improvement	Scopus
Ha et al. (2023)	Vietnam	A-5E-STEM (Argumentation-supported)	Quasiexperimental	120, grade 6	HOTS (analyze, evaluate, create)	Post-test & questionnaires	A-5E-STEM outperformed 5E-STEM & didactic, improved HOTS	Scopus
Asrizal et al. (2022)	Indonesia	Physics E-module (PETMS)	Experimental (nonequivalent)	66, secondary physics	CT, creative thinking, communication	Concept mastery test; skills assessment	PETMS improved 21st-century skills, incl. CT	Scopus
Hebebci & Usta (2022)	Turkey	STEM Science Grade 8	Quasiexperimental	50, grade 8	CT dispositions, PS, creativity	ANCOVA of pre/post data	CT and PS significantly improved	Scopus
Yim et al. (2024)	Hong Kong	Underwater Robotics PjBL	Design-based	Secondary (competition participants)	CT & problem-solving	Activity tasks; observation sheets	Robotics-enhanced CT, collaboration	Scopus
Rosidin et al. (2019)	Indonesia	STEM-HOTS Model	R&D + quasiexperimental	~54 students	HOTS (analyze, evaluate, create)	Pre-post HOTS tests	HOTS improved significantly vs. conventional	Google Scholar
Ananda et al. (2021)	Indonesia	Inquiry + STEM	Quasiexperimental (factorial)	63, high school chemistry	CT (reasoning, problem-solving)	Two-way ANOVA on the CT test	Significant gains in CT depending on initial ability	Google Scholar
Evcim & Arslan (2022)	Turkey	Force & Energy Unit (STEM)	Quasiexperimental	50, grade 7	CT (interpretation, explanation, evaluation)	Critical Thinking Scales (Demir, 2006a)	Significant CT gains in exp. group	Google Scholar
Prastika et al. (2022)	Indonesia	PBL-STEM (chemistry)	Quasiexperimental (2x2 factorial)	High school students	CT (conceptual, analytical)	CT & conceptual tests	PBL-STEM > PBL alone, improved CT across groups	Google Scholar
Puspita et al. (2022)	Indonesia	STEM-Fishbone diagram	Quasiexperimental	2 classes, SMA Bandar Lampung	CT & self-efficacy	CT test; MANOVA	Significant improvement in CT and self-efficacy	Google Scholar
Pramasdyahsari et al. (2023)	Indonesia	Digital Book STEM-PjBL	One-group pre-post	Junior high (math, number patterns)	Mathematical CT	Mathematical CT test; surveys	Valid & effective; medium N-gain in CT	Google Scholar
Ata et al. (2023)	Indonesia	PBL-STEM (Reaction Rate)	True experimental	High school chemistry	CT (analytical reasoning, problem-solving)	CT post-test; observation; questionnaires	PBL-STEM improved CT significantly	Google Scholar
Khoirunnissa et al. (2024)	Indonesia	STEM-PBL (Temp & Heat)	Preexperimental (one-group)	36, SMA	CT (clarification, reasoning)	Formative CT tests	Medium N-gain (0.5); CT improved overall	Google Scholar

Ashari et al. (2021)	Indonesia	PjBL-STEM (Biology)	One-group pre-post	32, SMA Malang	HOTS (Marzano taxonomy)	HOTS test (Marzano)	Significant gains in HOTS indicators	Google Scholar
Harianty et al. (2025)	Indonesia	STEM-PBL (Physics Kinematics)	Quasiexperimental	Grade XI SMA	CT (interpretation, synthesis, evaluation)	CT tests; N-gain; effect size	Very large effect (d = 2.07), N-gain = 0.57 (moderate)	Google Scholar
Rohmah et al. (2023)	Indonesia	STEM-GeoGebra PjBL (Math)	One-group pre-post	33, SMP Surabaya	CT (mathematical reasoning)	CT test; questionnaire	N-gain = 0.42 (medium), positive student responses	Google Scholar

Findings By Research Question

RQ1: What are the characteristics and trends of studies investigating iSTEM and CT?

The analysis revealed a clear growth in iSTEM research targeting CT and HOTS from 2019 onwards. Out of the 17 included studies, the majority were conducted in Indonesia, with additional contributions from Vietnam, Turkey, the United States, and Hong Kong. This regional concentration reflects particularly strong research activity in Southeast Asia, although it also indicates an imbalance in global evidence generation. Methodologically, quasi-experimental designs dominate, followed by mixed-methods, one-group pre-post, and a smaller number of true experiments and case studies. Sample sizes were generally modest (30-120 students). While the prevalence of classroom-based interventions demonstrates strong applied interest, the scarcity of Randomized Controlled Trials (RCTs) and longitudinal studies limits causal inference and understanding of sustained effects.

RQ2: What teaching approaches and strategies in iSTEM are reported to develop CT?

Across the reviewed studies, Project-Based Learning (PjBL) and Problem-Based Learning (PBL) emerged as the most effective and frequently used pedagogical approaches. These approaches are grounded in constructivist learning theory, encouraging inquiry, collaboration, and real-world problem-solving. Variations such as argumentation-supported models (A-5E-STEM), digital e-modules, GeoGebra-based mathematics instruction, and robotics-based STEM projects also demonstrated consistent positive impacts on CT development. Importantly, interventions that integrated explicit scaffolds, such as structured argumentation, fishbone diagrams, or AI-driven reflection, produced more robust CT outcomes compared to approaches where CT was assumed to emerge implicitly through STEM engagement.

RQ3: To what extent is iSTEM shown to be effective in enhancing students' CT?

Evidence strongly supports the effectiveness of iSTEM in fostering CT and HOTS among secondary school students. Sixteen out of the seventeen included studies reported significant improvements in CT indicators, including inference, evaluation, reasoning, explanation, and problem-solving. Several studies documented moderate-to-high normalized gains (0.3-0.57) and large effect sizes (Cohen's $d > 0.8$), indicating substantial impact. Even in studies where no statistical significance was observed (e.g., Thomason & Hsu, 2025), students perceived positive benefits in design thinking, collaboration, and problem-solving. These findings confirm that iSTEM interventions are generally effective in improving CT, although the strength of outcomes varies depending on intervention duration, instructional quality, and the presence of explicit scaffolding.

RQ4: What gaps and recommendations emerge from the existing literature?

Despite encouraging findings, several research gaps remain. First, the dominance of short-term quasiexperimental studies highlights the need for more rigorous longitudinal and randomized designs to establish sustained effects and causal claims. Second, teacher readiness and professional development remain critical challenges. Many teachers lack sufficient preparation to implement interdisciplinary iSTEM effectively. Third, there is a lack of standardized CT assessment tools, as studies employ diverse instruments (e.g., CT scales, HOTS tests, self-report surveys), making comparison across contexts difficult. Finally, the regional clustering of studies, particularly in Indonesia, underscores the need for broader representation from other global regions, such as Europe, Africa, and Latin America, to build a more balanced evidence base.

DISCUSSIONS

This review reveals a steady growth in research on iSTEM and CT over the past decade, with the majority of studies conducted in Asian contexts and employing experimental or quasi-experimental designs. This trend reflects a global shift toward evidence-based instructional models, as noted in prior meta-analytic work (Becker & Park, 2011), which also reported medium-sized positive effects of STEM integration on student outcomes.

Findings related to RQ2 indicate that PjBL, robotics, and Design-Based Inquiry were among the most frequently employed and effective pedagogical approaches. These strategies align with constructivist and design-based learning theories, which emphasize authentic problem-solving and student-centered inquiry (Thomas & Larwin, 2023). The strong gains in CT observed in studies using explicit scaffolding (e.g., guiding questions, structured reflection, or AI-supported feedback) further highlight the importance of intentional design in fostering higher-order reasoning.

Regarding RQ3, approximately 94% of included studies (16 of 17) reported statistically significant improvements in CT or HOTS following iSTEM interventions. This aligns with recent reviews suggesting that well-designed STEM interventions reliably produce cognitive gains, although the magnitude of effects varies depending on duration, teacher preparation, and assessment quality (Thomas & Larwin, 2023). Interventions of longer duration and those embedding explicit critical-thinking activities yielded stronger N-Gain or effect size values.

Nevertheless, the analysis highlights several gaps (RQ4). Many studies used small samples or lacked control groups, limiting the generalizability of findings. There was also an inconsistency in the operationalization and measurement of CT, with some relying solely on teacher-made tests or rubric-based assessments. These methodological limitations echo calls from prior reviews for more robust research designs and standardized CT assessments (Fatimah et al., 2023). Furthermore, the limited attention to teacher readiness and implementation fidelity in the reviewed studies suggests that future research should explore student outcomes and consider how instructional materials and teaching supports can enhance the practicality of iSTEM approaches. In addition, strengthening these dimensions would ensure that iSTEM interventions are effective in theory, as well as sustainable and applicable in real classroom contexts.

CONCLUSION

This systematic review of 17 empirical studies published between 2019 and 2025 demonstrates that iSTEM approaches are largely effective in enhancing secondary school students' CT. The most successful interventions integrated real-world problem-solving, inquiry-based learning, and collaborative design tasks, particularly through PjBL, PBL, and robotics-based STEM projects.

Despite these promising outcomes, several areas require further attention. Many studies remain short-term and quasi-experimental, limiting causal inferences. The lack of standardized CT assessments and limited teacher readiness also constrain broader implementation. Future research should therefore focus on longitudinal and randomized studies, develop common measurement frameworks for CT, and provide systematic professional development to enhance teachers' capacity to deliver high-quality iSTEM instruction.

By addressing these gaps, iSTEM education can serve as a sustainable and evidence-based pathway for cultivating students' critical skills and HOTS essential for 21st-century learning.

ACKNOWLEDGMENT

The authors declare that this research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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