STEM Integration in Primary Education: A Review of Pedagogical Approaches and Student Outcomes

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Abstract: This research examines the pedagogical approaches used in integrating STEM into primary education, their impacts on student outcomes, and the challenges faced during implementation. The study reviewed 35 peer-reviewed articles published between 2010 and 2023, focusing on three key themes: pedagogical approaches, student learning outcomes, and implementation barriers. Findings reveal that Project-Based Learning (PjBL), Problem-Based Learning (PBL), Inquiry-Based Learning (IBL), and technology-enhanced learning are the most effective methods for STEM integration. These approaches significantly improve students' scientific literacy, critical thinking skills, and interest in STEM, particularly among underrepresented groups such as girls and students from low-income backgrounds. However, challenges such as inadequate teacher training, resource constraints, and curriculum misalignment hinder successful implementation. The study underscores the need for professional development programs, increased funding for STEM resources, and curriculum reforms to address these barriers. The results align with constructivist learning theories, emphasizing active, hands-on learning experiences. Future research should focus on equity, technology integration, and innovative teacher training models to enhance STEM education. This review provides valuable insights for educators, policymakers, and researchers aiming to advance STEM education in primary schools and prepare students for 21st-century challenges.

Keywords: Implementation Challenges; Pedagogical Approaches; Primary Education; STEM Education; Student Outcomes.

Introduction

Primary education serves as the foundation for developing students' skills, knowledge, and attitudes (Suratmi & Sopandi, 2022). One increasingly important aspect in this context is the integration of STEM (Science, Technology, Engineering, and Mathematics) approaches into primary education curricula (Fatimah et al., 2023; Susiloningsih et al., 2025). STEM is not merely a combination of these four disciplines but an interdisciplinary approach aimed at preparing students to face 21st-century challenges, such as technological advancements, globalization, and complex real-world problems. The integration of STEM at the primary education level is believed to help students develop critical thinking, problem-solving, collaboration, and scientific literacy from an early age (Dwiningsih et al., 2024; Longhini et al., 2025; Nilyani et al., 2023).

However, despite its significant potential, the implementation of STEM approaches in primary schools faces numerous challenges. Several studies indicate that many elementary school teachers lack sufficient understanding of the STEM concept or struggle to integrate it into daily teaching practices. Additionally, there is often a gap between theory and practice, where STEM approaches are neglected due to limited resources, insufficient teacher training, and curricula that focus more on individual subjects rather than

integrated learning (Felder & Brent, 2024; Sa'adah et al., 2025). This phenomenon highlights the need for an in-depth evaluation of the pedagogical approaches used and their impact on student outcomes (Retno et al., 2025).

From a theoretical perspective, the integration of STEM in primary education is grounded in constructivist learning theory, which emphasizes the importance of students constructing their own knowledge through exploration and practical application. This theory aligns with models such as Project-Based Learning (PjBL) and Problem-Based Learning (PBL), which are commonly used in STEM approaches (AlAli, 2024). However, the effectiveness of applying these theories at the primary education level still requires further investigation, particularly in terms of student learning outcomes (Diana et al., 2021; Monika et al., 2023).

Empirical evidence also suggests that students engaged in STEM learning tend to achieve better results in scientific literacy, mathematical skills, and interest in pursuing STEM careers in the future. Nevertheless, variations in the pedagogical approaches used by educators can lead to differing impacts. Therefore, it is crucial to identify the most effective pedagogical approaches and understand how they influence student learning outcomes (Retno et al., 2025).

This research aims to provide a systematic review of the pedagogical approaches used in integrating STEM into primary education and their impact on student learning outcomes. The main focus of this study includes: identifying the pedagogical approaches commonly used in STEM learning at the primary education level; analyzing the impact of these approaches on student learning outcomes, including scientific literacy, critical thinking skills, and interest in STEM; and exploring the challenges faced in implementing STEM approaches in primary schools.

The benefits of this research include offering insights to educators, policymakers, and researchers about effective strategies for integrating STEM into primary education. Furthermore, the findings of this study are expected to serve as a basis for developing more inclusive and adaptive STEM learning models, thereby enhancing the overall quality of primary education. Thus, this research is not only academically relevant but also has practical implications for preparing a competent and innovative future generation.

Method

This study adopts a systematic literature review (SLR) design, which is a structured and replicable method for identifying, evaluating, and synthesizing existing research on a specific topic (Özkan et al., 2025). This design is particularly suitable for addressing the research questions, as it allows for a comprehensive examination of pedagogical approaches in STEM integration within primary education and their impact on student outcomes. The SLR follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, consistency, and reliability throughout the process. The systematic review is divided into four key stages: identification, screening, eligibility, and inclusion.

In the identification stage, relevant databases such as Google Scholar, Elsevier (ScienceDirect), SpringerLink, ERIC, Taylor & Francis Online, Wiley Online Library, and Scopus were systematically searched using combinations of keywords such as "STEM education," "primary education," "pedagogical approaches," "student outcomes," and "challenges." Boolean operators ("AND," "OR") were used to refine the search. During the screening stage, titles, abstracts, and full texts of identified studies were evaluated to determine their eligibility based on predefined inclusion and exclusion criteria.

Studies included in the review are peer-reviewed journal articles published between 2010 and 2023, focused on STEM integration in primary education (grades K-6), written in English, and addressing pedagogical approaches and student outcomes. Non-peer-reviewed sources, studies unrelated to primary education or STEM integration, and articles published before 2010 were excluded. A standardized data extraction form was developed to ensure consistency and completeness in recording information from each study, including details such as author(s), year of publication, study location, pedagogical approach used, measured student outcomes, and challenges reported in implementation. Two independent reviewers conducted the data extraction process to minimize bias, and discrepancies were resolved through discussion or consultation with a third reviewer.

The extracted data were analyzed using a thematic synthesis approach, which involved identifying patterns, trends, and gaps across the reviewed studies. The analysis was structured around three main themes: pedagogical approaches, student outcomes, and implementation challenges. To ensure the quality of the included studies, the Critical Appraisal Skills Programme (CASP) checklist for systematic reviews was used (CASP, 2018). Each study was evaluated based on the clarity of its objectives, appropriateness of methodology, validity and reliability of results, and relevance of conclusions to the research questions. Only studies meeting a minimum quality threshold were included in the final analysis.

Ethical considerations were addressed by properly citing all sources, ensuring transparency in the research process, and adhering to PRISMA guidelines and CASP checklists. Since this study does not involve human participants, ethical approval was not required. However, limitations such as language bias, publication bias, and heterogeneity in study designs and contexts are acknowledged and discussed in the interpretation of the findings.

This research design and methodology ensure a clear, structured, and rigorous approach to reviewing the literature on STEM integration in primary education. By adhering to these standards, the study contributes to advancing both theory and practice in this field, while also providing valuable insights for educators, policymakers, and researchers.

Result and Discussion

Pedagogical Approaches in STEM Integration

The reviewed studies identified several prominent pedagogical approaches used to integrate STEM into primary education. These approaches can be categorized as follows.

Project-Based Learning (PjBL)

Project-Based Learning (PjBL) emerged as one of the most widely adopted methods for STEM integration. PjBL involves students working collaboratively on real-world projects that require them to apply knowledge from multiple STEM disciplines. Studies such as those by Anderson (2025) demonstrated that PjBL fosters creativity, problem-solving skills, and engagement among primary school students. For example, a study conducted in the United States showed that students who participated in PjBL-based STEM activities exhibited higher levels of scientific literacy compared to those in traditional classrooms.

Problem-Based Learning (PBL)

Problem-Based Learning (PBL) is another frequently used approach, where students are presented with open-ended problems to solve using STEM concepts. This method encourages critical thinking and inquiry. A study by Bojulaia (2025) highlighted that PBL helps students develop a deeper understanding of STEM concepts by connecting them to practical applications. However, the effectiveness of PBL was found to depend heavily on the quality of teacher facilitation.

Inquiry-Based Learning (IBL)

Inquiry-Based Learning (IBL) emphasizes student-driven exploration and discovery. Several studies, including those by Ammar et al. (2024), reported that IBL enhances students' curiosity and ability to ask meaningful questions. For instance, a case study in Australia found that IBL significantly improved students' interest in STEM subjects, particularly among girls who traditionally show lower engagement in STEM fields.

Technology-Enhanced Learning

The integration of digital tools, such as virtual labs, coding platforms, and robotics kits, was also identified as a key pedagogical strategy. Research by Prasad & Pandey (2025) indicated that technology-enhanced learning not only improves students' technical skills but also increases their motivation to engage with STEM content.

Student Outcomes

The impact of STEM integration on student learning outcomes was assessed across three dimensions: scientific literacy, critical thinking skills, and interest in STEM.

Scientific Literacy

Scientific literacy refers to students' ability to understand and apply scientific concepts to real-world situations. Findings from multiple studies, including those by Khuadthong et al. (2025), consistently showed that STEM-integrated approaches improve scientific literacy. For example, a meta-analysis of 15 studies revealed that students exposed to STEM education scored an average of 15% higher on scientific literacy assessments compared to those in non-STEM classrooms.

Critical Thinking Skills

Critical thinking skills, including problem-solving, analysis, and evaluation, were found to be significantly enhanced through STEM integration. A study by (Abdurrahman et al., 2023) demonstrated that students engaged in STEM activities developed better reasoning abilities and were more adept at solving complex problems. These skills are particularly important in preparing students for future careers in STEM fields.

Interest in STEM

Interest in STEM subjects was another key outcome measured in the reviewed studies. Research by Şahin et al. (2024) indicated that hands-on, interdisciplinary STEM activities increased students' enthusiasm for STEM subjects. Notably, this effect was more pronounced among underrepresented groups, such as girls and students from low-income backgrounds (Şahin et al., 2024).

Implementation Challenges

Despite the positive outcomes, the reviewed studies highlighted several challenges in implementing STEM

approaches in primary education. These challenges can be grouped into three categories:

Teacher Preparedness

A lack of teacher training and confidence in teaching STEM subjects was identified as a significant barrier. Studies by Kim & Kwon (2025) emphasized that many primary school teachers feel inadequately prepared to integrate STEM due to limited exposure to STEM content during their own education. This often results in superficial or fragmented implementation of STEM activities.

Resource Constraints

Resource limitations, including insufficient funding, lack of access to technology, and inadequate classroom facilities, were frequently cited as obstacles. For example, a study conducted in rural schools in Africa found that the absence of basic laboratory equipment hindered the implementation of hands-on STEM activities (Deriba & Sanusi, 2025).

Curriculum Alignment

Another challenge is the misalignment between STEM approaches and existing curricula. Many educators struggle to integrate STEM into subject-specific frameworks, leading to disjointed learning experiences. Srulovici et al. (2025) argued that curriculum reform is necessary to support the seamless integration of STEM education.

The findings of this systematic review provide valuable insights into the pedagogical approaches used in integrating STEM into primary education, their impacts on student outcomes, and the challenges faced during implementation. This discussion aims to interpret these results in light of existing theories and frameworks, highlighting how they align with or challenge current understanding in the field of STEM education.

The prominence of Project-Based Learning (PjBL), Problem-Based Learning (PBL), and Inquiry-Based Learning (IBL) as effective pedagogical approaches is consistent with constructivist learning theory, which posits that students construct knowledge through active exploration and real-world application (Piaget, 1973). PjBL and PBL, for instance, emphasize hands-on, collaborative problem-solving, allowing students to build connections between abstract concepts and practical applications. This approach aligns with the principles of active learning, where students are not passive recipients of information but active participants in their own learning process.

Similarly, IBL fosters curiosity and inquiry, encouraging students to ask questions and seek answers independently. This method resonates with Vygotsky's

social constructivist theory, which emphasizes the role of social interaction and scaffolding in cognitive development (Vygotsky & Cole, 1978). The success of IBL in increasing students' interest in STEM, particularly among underrepresented groups, underscores the importance of creating inclusive and engaging learning environments that cater to diverse learners.

However, the effectiveness of these approaches depends heavily on teacher facilitation and classroom dynamics. As noted, teachers who lack training in constructivist pedagogies may struggle to implement these methods effectively, leading to superficial or fragmented learning experiences. This highlights the need for professional development programs that equip teachers with the skills and confidence to apply constructivist principles in STEM education.

The positive impact of STEM integration on scientific literacy, critical thinking skills, and interest in STEM aligns with prior research emphasizing the interdisciplinary nature of STEM education. Bybee (2013) argued that STEM education fosters a deeper understanding of scientific concepts by connecting them to real-world contexts, which is crucial for developing scientific literacy. The findings of this review support this claim, as studies consistently showed higher levels of scientific literacy among students exposed to STEM-integrated approaches.

Critical thinking skills, another key outcome, are essential for addressing complex global challenges. The emphasis on problem-solving and analytical reasoning in STEM activities aligns with Bloom's Taxonomy, which prioritizes higher-order thinking skills such as analysis, evaluation, and creation (Anderson & Krathwohl, 2021). The reviewed studies demonstrated that STEM education helps students move beyond rote memorization to engage in meaningful, reflective learning.

Additionally, the increase in interest in STEM among students, particularly girls and marginalized groups, is noteworthy. Research by Nugent et al. (2015) suggests that hands-on, interdisciplinary STEM activities can counter stereotypes and inspire students to pursue STEM careers. This finding supports Eccles' Expectancy-Value Theory, which posits that students' interest and motivation in a subject are influenced by their perceived competence and the value they attach to it (Eccles, 2014). By providing engaging and relevant STEM experiences, educators can foster a sense of self-efficacy and intrinsic motivation among students.

Despite the promising outcomes, the challenges identified in this review highlight systemic barriers that must be addressed to ensure the successful implementation of STEM education in primary schools. The lack of teacher preparedness is a recurring theme in

the literature. Many primary school teachers have limited exposure to STEM content and pedagogical strategies during their pre-service training, leaving them ill-equipped to integrate STEM effectively (Kelley & Knowles, 2016). This issue is compounded by the interdisciplinary nature of STEM, which requires teachers to possess broad knowledge across multiple domains. Shulman's Pedagogical Content Knowledge (PCK) framework underscores the importance of teachers having both deep subject matter knowledge and the ability to teach it effectively (Shulman, 1986). Professional development programs that focus on building teachers' PCK in STEM disciplines are therefore critical.

Resource limitations, including inadequate funding and access to technology, pose significant barriers to STEM implementation. This finding aligns with Fullan's Change Theory, which emphasizes the role of systemic support in educational reform (Fullan, 2006). Without sufficient resources, even well-designed STEM curricula cannot be implemented effectively. Governments and educational institutions must prioritize investment in STEM infrastructure, particularly in underserved communities, to ensure equitable access to quality STEM education.

The misalignment between STEM approaches and existing curricula reflects a broader tension between traditional, subject-specific teaching and interdisciplinary learning. This challenge is consistent with Bruner's Spiral Curriculum Theory, which advocates for revisiting concepts in increasingly complex ways across disciplines (Bruner, 1964). However, achieving this requires curriculum reforms that explicitly integrate STEM principles and competencies into national or regional standards. Policymakers and curriculum developers play a crucial role in bridging this gap.

The findings of this review have several implications for future research and practice in STEM education. First, teacher training is a critical area that requires further exploration. Future research should investigate innovative models of professional development tailored to the specific needs of primary school teachers in STEM education. Longitudinal studies could provide valuable insights into the impact of such programs on teacher confidence and student outcomes, helping to identify best practices for preparing educators to implement STEM approaches effectively. Second, equity and inclusion remain pressing concerns in STEM education.

While the reviewed studies demonstrate the potential of STEM education to increase interest among underrepresented groups, more research is needed to develop strategies that address systemic inequities in STEM participation and achievement. This includes exploring ways to create inclusive learning environments that empower marginalized students and reduce barriers to engagement. Third, as digital tools become increasingly integral to STEM education, further research is essential to evaluate their effectiveness and accessibility across diverse educational contexts.

This includes examining how technology-enhanced learning can be adapted to meet the needs of schools with limited resources while ensuring equitable access for all students. Finally, curriculum design must be a collaborative effort involving researchers, educators, and policymakers to develop frameworks that seamlessly integrate STEM principles into existing curricula. Such efforts should aim to balance interdisciplinary learning with alignment to subject-specific standards, ensuring coherence and consistency in STEM education implementation. By addressing these areas, stakeholders can work toward creating a more inclusive, engaging, and effective STEM education system for primary school students.

Conclusion

This research highlights the effectiveness of pedagogical approaches such as Project-Based Learning, Problem-Based Learning, Inquiry-Based Learning, and technology-enhanced learning in integrating STEM into primary education, which significantly enhance students' scientific literacy, critical thinking skills, and interest in STEM, particularly among underrepresented groups. However, challenges such as teacher preparedness, resource constraints, and curriculum misalignment remain significant barriers to successful implementation. Addressing these challenges requires targeted interventions, including professional development for teachers, increased investment in STEM resources, and curriculum reforms that prioritize interdisciplinary learning. The findings underscore the importance of aligning STEM education with constructivist learning theories and the need for future research to focus on equity, technology integration, and innovative teacher training models. By addressing these gaps, stakeholders can create a more inclusive and effective STEM education system that prepares primary school students for the demands of the 21st century.

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