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Integrating STEM Approaches in Elementary Science Education: Toward Meaningful Learning

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Abstract
STEM (Science, Technology, Engineering, and Mathematics) education has become a priority in preparing students with the skills needed for the 21st century. At the elementary level, where foundational scientific understanding is built, the challenge lies in ensuring that learning is not limited to factual recall but promotes meaningful engagement. Meaningful learning occurs when students connect new knowledge to prior understanding and real-life experiences, enabling them to think critically, solve problems, and retain concepts more effectively. This paper aims to explore how STEM approaches can be integrated into elementary science education to promote meaningful learning. An integrative literature review was conducted, analyzing 18 peer-reviewed studies published between 2015 and 2024. Data were gathered from Scopus, Google Scholar, and open-access journals using keywords such as "STEM in elementary education," "meaningful learning," and "inquiry-based STEM." Articles were thematically analyzed across four dimensions: problem-solving and critical thinking, teacher readiness and professional development, cultural and contextual relevance, and the role of technology. The findings indicate that STEM projects framed around real-world issues enhance students' problem-solving abilities, scientific literacy, and curiosity. Teachers' preparedness strongly influences whether STEM activities result in surface-level engagement or deeper understanding, highlighting the need for professional development. Integrating cultural practices and everyday contexts was found to strengthen relevance, while technology enriched learning when applied as a tool for inquiry rather than as an end in itself. In conclusion, integrating STEM in elementary science fosters meaningful learning by connecting inquiry, culture, teacher capacity, and technology. This approach equips young learners with not only scientific knowledge but also the skills and dispositions essential for lifelong learning.

Keywords:
STEM education;
Elementary science;
Meaningful learning;
Problem-solving;
Inquiry-based learning

1. Introduction

STEM (Science, Technology, Engineering, and Mathematics) education has emerged as a pivotal approach within 21st-century classrooms, promoting essential skills such as problem-solving, creativity, and collaboration among elementary school students (Kelana et al., 2024). The significance of integrating STEM disciplines at the elementary level lies in establishing a strong foundation in these areas, which is fundamental for students to progress to more sophisticated concepts as they advance in their education (Hoeg & Bencze, 2017). However, despite the widespread advocacy for STEM education, many implementations tend to prioritize rote content knowledge and project activities without adequately ensuring that learners experience meaningful connections to the material (LaForce et al., 2016).

Meaningful learning, which involves linking new information with prior knowledge and real-world experiences (Hafidzoh et al., 2023; Sudirman et al., 2022; 2023; 2024), is particularly important in STEM as it helps students construct relevant and lasting understandings of complex concepts (Lamberg & Trzynadlowski, 2015). By incorporating experiences from students' everyday lives into the learning process, educators can significantly enhance engagement and retention of scientific ideas (Radloff & Güzey, 2017), ultimately leading to a deeper, more enriching educational experience. However, challenges such as teacher readiness, insufficient curricular resources, and a lack of coherent instructional models often impede the realization of meaningful learning within STEM contexts (Sukiyani, 2023). This paper will explore effective strategies for integrating STEM learning that foster meaningful educational outcomes, addressing the need for teachers to design instruction that connects abstract concepts with practical applications in students' lives.

The integration of innovative pedagogical strategies into elementary education, such as experiential learning (EL) and STEM project-based learning (PBL), has significant implications for meaningful learning. Research indicates that students derive greater engagement and understanding when they can connect classroom content with real-world applications. Studies have shown the effectiveness of experiential approaches that allow students to engage actively with material, enhancing retention and understanding of content (Yusof et al., 2020; (Le et al., 2023). These strategies facilitate a deep learning experience, enabling students to discern the relevance of their education by applying learned concepts to tangible problems encountered in life.

Despite its potential, research also highlights significant challenges in the implementation of STEM at the elementary level. Teachers often acknowledge the benefits of STEM—such as promoting independence, engagement, and problem-solving—but report low levels of readiness to integrate it into their daily practice (Susanti et al., 2020; Sukiyani, 2023; Shidiq & Nasrudin, 2021). Similarly, cross-national studies, such as those in Vietnam, reveal limited teacher confidence and preparation, suggesting that this issue is global (Anh et al., 2023). At the same time, contextual approaches, such as embedding STEM in environmental projects or local culture, have been found to support comprehension and meaningful engagement (Andriani et al., 2020; Tsoukala, 2021; Eshaq, 2023). However, not all schools are able to provide adequate resources, technology, or professional development to ensure effective STEM integration (Galindo & Aguilar, 2019; Wright et al., 2018; Havice et al., 2018). This situation leads to inconsistent implementation and highlights the need for systematic frameworks that make STEM accessible, relevant, and sustainable at the elementary level.

Previous studies have largely examined STEM in three directions: (1) general frameworks and policy discussions (Saw, 2020; Chestnutt, 2022; Natarajan et al., 2021); (2) informal or extracurricular STEM experiences that expand perceptions of STEM careers (Roberts et al., 2018; Hurst et al., 2019); and (3) secondary or higher education contexts with a focus on technology and equity (Hsu et al., 2016; Daher & Shahbari, 2020; Cherniak et al., 2019). While these contributions are valuable, they do not fully address how STEM integration in elementary science education specifically promotes meaningful learning. In particular, there is limited synthesis of how STEM fosters meaningful learning by helping students connect prior knowledge with new concepts, by embedding cultural and contextual relevance, and by enabling collaborative, inquiry-driven activities. This gap indicates the need for a comprehensive review that focuses on elementary school science education, where building meaningful understanding is crucial for long-term academic success.

Therefore, this study aims to analyze and synthesize current literature on the integration of STEM approaches in elementary science education to determine how such integration promotes meaningful learning. The guiding problem formulation of this research is: *In what ways does STEM integration in elementary education foster meaningful learning, and what conditions are necessary to ensure its effective implementation*? By addressing this question, the study provides both theoretical insights and practical implications for strengthening elementary science education through meaningful STEM learning.

2. Method

This study employed a qualitative integrative literature review to synthesize empirical and conceptual studies on the integration of STEM approaches in elementary science education and their role in promoting meaningful learning. An integrative review was selected to accommodate diverse research designs and provide a comprehensive understanding of STEM implementation across educational contexts. Literature searches were conducted on 20 September 2024 using Scopus, Google Scholar, and selected open-access educational journals. Search terms included *"STEM in elementary education," "meaningful learning," "STEM project-based learning,"* and *"science literacy."* Boolean operators (AND, OR) were used to refine results. The initial search yielded 25 articles.

Article selection followed predefined inclusion and exclusion criteria to ensure relevance and rigor.

Inclusion criteria: (1) publication between 2015 and 2024; (2) peer-reviewed journal articles or refereed conference proceedings; (3) focus on STEM implementation in elementary or primary school contexts; (4) explicit discussion of meaningful learning outcomes (e.g., problem-solving, inquiry, critical thinking, collaboration, contextual learning, or science literacy); (5) availability of full-text articles in English or Bahasa Indonesia. Exclusion criteria: (1) studies limited to secondary or higher education; (2) policy- or theory-only discussions without classroom implementation;(3) informal STEM learning contexts without clear links to elementary science instruction; (4) studies emphasizing leadership, equity, or technology without connection to meaningful learning; (5) non-peer-reviewed sources or incomplete publications. After screening, 18 articles met the criteria and were retained for analysis.

A quality assessment was conducted to ensure methodological soundness and relevance. Each study was appraised using a structured checklist covering: (1) clarity of research purpose, (2) methodological rigor, (3) relevance to elementary science learning, and (4) contribution to meaningful learning outcomes. Each dimension was rated as high, moderate, or low. Only studies rated high or moderate across all dimensions were included. Studies with limited methodological clarity or weak alignment with meaningful learning were excluded.

The selected studies were analyzed thematically. Open coding identified key concepts related to meaningful STEM learning, followed by axial coding to cluster findings into four themes: (1) problem-solving and critical thinking, (2) teacher readiness and professional development, (3) cultural and contextual relevance, and (4) technology and multimodal engagement. These themes guided the synthesis of findings on how STEM integration supports meaningful learning in elementary science education.

3. Results and Discussion

3.1 Results

The systematic review identified 18 articles that met the inclusion criteria. These studies represent a range of contexts and approaches, but together they provide valuable insights into how STEM integration in elementary science education promotes meaningful learning. The key findings are summarized in Table 1.

Table 1

Summary of Reviewed Articles on STEM Integration in Elementary Science Education

Author(s) & Year	Focus / Context	Key Findings	Relevance to Meaningful Learning in Elementary Science
Kelana et al. (2024)	STEM + environmental issues in elementary	Stimulates interest, fosters long-term understanding, enhances problem-solving.	Contextual science issues help drive meaningful STEM integration.
Sujud et al. (2024)	STEM-PjBL integrated with matter state changes	Improves science literacy through contextual projects.	Direct connection between STEM projects and science content.
Awaludin et al. (2024)	STEM + self-efficacy	Positive impact on outcomes; confidence motivates problem-solving.	Links confidence with meaningful engagement in science tasks.

Author(s) & Year	Focus / Context	Key Findings	Relevance to Meaningful Learning in Elementary Science
Sukiyani (2023)	Teachers' challenges (Indonesia, elementary)	Enthusiasm exists, but readiness gaps remain.	Teacher readiness is a condition for meaningful STEM learning.
Suciana et al. (2023)	Meta-analysis: PBL + STEM	Increases learning activities, scientific attitudes, and outcomes.	Strong evidence for PBL-STEM as a pathway to meaningful science learning.
Marsari & Rifma (2023)	STEM-based teaching materials (grade III)	Improved science literacy and contextual understanding.	Demonstrates materials design for meaningful learning.
Eshaq (2023)	STEM in mathematics achievement	Real-life applications foster enjoyment and critical thinking.	Supports integration of math in science contexts.
Tsoukala (2021)	Multimodal STEM in early education	Inquiry/play-based approaches support knowledge representation.	Early foundations of meaningful science learning.
Shidiq & Nasrudin (2021)	Teacher readiness for STEM	Teachers struggle with contextual integration and resources.	Confirms readiness as a challenge for science-focused STEM.
Anh et al. (2023)	Vietnamese primary teachers' awareness/confidence	Limited preparedness despite recognizing STEM potential.	Reinforces PD needs for science integration.
Andriani et al. (2020)	Math + culture (local context)	Cultural approaches improve comprehension and relevance.	Provides model for culturally responsive STEM science.
Susanti et al. (2020)	Teachers' perspectives on STEM in elementary	Teachers value outcomes, but few feel prepared.	Reveals the gap between perceived benefits and readiness.
Galindo & Aguilar (2019)	Teacher perceptions of STEM PD (elementary)	PD and confidence shape instructional strategies.	Highlights teacher training as key to meaningful STEM.
Hakim et al. (2019)	STEM-PjBL in mathematics	Builds logical thinking, innovation, independence.	Useful for linking math and science learning.
Cherniak et al. (2019)	Early childhood robotics	Children design robotic solutions to real-life problems.	Hands-on inquiry supports problem-solving and science engagement.
Lamberg & Trzynadlowski (2015)	Teachers conceptualizing STEM	Hands-on, project-based approaches improve outcomes.	Validates inquiry-based, practical STEM in classrooms.
Zainil et al. (2022)	STEM-based digital classroom (Indonesia, elementary)	Improves collaboration, communication, creativity.	Shows how digital STEM enhances 21st-century science learning.
Kelley & Knowles (2016)	Framework for integrated STEM	Interdisciplinary, inquiry-based connections sustain engagement.	Provides theoretical basis for meaningful integration in science.

Analysis of the reviewed studies revealed four major themes in how STEM fosters meaningful learning in elementary science education.

Problem-Solving and Critical Thinking

The literature consistently suggests that STEM-based projects can create conditions for meaningful learning, as they engage students in linking new knowledge with real-world experiences. Kelana et al. (2024) reported that environmental issues used in science learning increased students' interest and supported their analytical development. Sujud et al. (2024) similarly emphasized that projects exploring changes in the states of matter fostered science literacy, a crucial foundation for meaningful understanding. Awaludin et al. (2024) added that self-efficacy contributes to this process, since confidence enables students to take risks and try new solutions. These studies collectively indicate that meaningful learning occurs when elementary students are encouraged to actively problem-solve, build connections between abstract concepts and authentic contexts, and gain confidence in applying their knowledge.

Teacher Readiness and Professional Development

Teacher capacity emerges as a decisive factor in realizing meaningful learning through STEM. Although teachers generally acknowledge STEM's benefits, many feel unprepared to implement it in practice (Susanti et al., 2020; Sukiyani, 2023; Shidiq & Nasrudin, 2021). Similar findings in Vietnam (Anh et al., 2023) confirm that limited preparedness can constrain students' opportunities for deep, meaningful engagement with science content. However, professional development has been shown to strengthen teacher confidence and strategies (Galindo & Aguilar, 2019), which in turn supports learning experiences that go beyond rote instruction. Meaningful learning in STEM depends not only on curriculum design but also on teachers' ability to guide inquiry, encourage connections to prior knowledge, and sustain student engagement.

Cultural and Contextual Relevance

A recurring theme in the literature is that STEM becomes more meaningful when linked to students' cultural backgrounds and daily lives. Andriani et al. (2020) demonstrated that embedding mathematics in local cultural practices improved comprehension, while Eshaq (2023) observed that connecting mathematics to real-life contexts made learning more enjoyable and critical. Tsoukala (2021) further showed that multimodal, play-based approaches supported children's knowledge representation in ways that resonate with meaningful learning principles. These findings imply that meaningful learning is strengthened when new science concepts are not presented in isolation but are anchored in students' lived experiences, allowing them to integrate and retain knowledge more effectively.

Technology and Multimodal Engagement

Technology also plays a significant role in enabling meaningful learning. Zainil et al. (2022) found that digital STEM classrooms promoted collaboration, communication, and creativity, while Cherniak et al. (2019) revealed that young children designing robotic solutions gained authentic opportunities to connect learning with real-world challenges. Hsu et al. (2016) highlighted that augmented reality could spark curiosity and sustain interest in STEM. These studies suggest that technology can deepen meaningful learning by making abstract science ideas visible, interactive, and engaging. Still, disparities in access mean that meaningful integration of technology must be carefully adapted to the resources available in different school contexts.

3.2 Discussion

This study set out to examine how integrating STEM approaches in elementary science education contributes to meaningful learning, and the findings provide strong support for this aim. The evidence demonstrates that STEM fosters meaningful learning by embedding knowledge in real-world contexts, cultivating inquiry and collaboration, bridging cultural relevance, and leveraging technology. Taken together, these elements suggest that STEM is not simply a method of teaching multiple disciplines together, but rather a pedagogical framework for enabling students to construct knowledge in ways that are relevant, enduring, and applicable (Kelley & Knowles, 2016; Tsoukala, 2021).

A central outcome of this review is the clear link between STEM integration and problem-solving in authentic contexts. When science lessons are framed around environmental or everyday issues, students not only develop scientific literacy but also learn to connect abstract concepts with practical applications. For example, a class might explore the science of clean water by designing simple filters using local materials. This reflects findings that contextualized STEM projects enhance problem-solving and scientific reasoning in elementary learners (Kelana et al., 2024; Sujud et al., 2024). Moreover, the inclusion of self-efficacy—students' belief in their own abilities—has been shown to further strengthen engagement and willingness to attempt innovative solutions (Awaludin et al., 2024). Meaningful learning, therefore, occurs when inquiry is not only cognitively demanding but also empowering for the learner.

Another important dimension is the role of teachers' readiness and professional development. The review highlights a consistent gap between the potential of STEM and the confidence teachers feel in enacting it. This finding suggests that meaningful learning depends less on the inherent promise of STEM, and more on the capacity of teachers to guide inquiry effectively (Susanti et al., 2020; Anh et al., 2023). For instance, a well-prepared teacher might transform a unit on plant growth into a hands-on garden inquiry, whereas a less confident teacher may fall back on lecture-style explanations. These differences align with earlier studies noting that teacher agency and professional development are central to whether STEM learning becomes truly meaningful (Galindo & Aguilar, 2019; Natarajan et al., 2021). The variation across classrooms underscores that building teacher capacity is not an optional extra but a prerequisite for STEM's success.

The findings also underscore the value of cultural and contextual grounding in promote meaningful learning. When STEM is connected to local traditions, practices, or everyday experiences, students are more likely to internalize concepts and see their relevance (Andriani et al., 2020). For example, linking states of matter to traditional food preparation or using local crafts to teach measurement makes abstract science more tangible. This aligns with theories of meaningful learning, which stress that new knowledge is most powerful when integrated with existing experiences (Hafidzoh et al., 2023). By rooting STEM in culture, science learning is not perceived as distant or abstract, but as part of children's lived worlds.

Finally, the role of technology and multimodal tools appears to amplify meaningful learning. Digital classrooms, coding activities, or robotics projects not only make abstract concepts visible but also create opportunities for collaboration and experimentation. Evidence shows that augmented reality, for example, can increase students' interest and deepen their understanding of science concepts by making invisible processes visible (Hsu et al., 2016; Zainil et al., 2022). Importantly, technology functions best as a catalyst for inquiry-driven learning, not as a replacement for thinking. A simple application might be using AR apps to "see inside" a plant cell, transforming a static diagram into an immersive experience that anchors new knowledge in curiosity and wonder. This suggests that technology should be integrated not as a flashy add-on, but as a catalyst for inquiry-driven, meaningful learning.

The findings of this study provide clear direction for elementary education practice. To promote meaningful learning through STEM:

1) Design Inquiry- and Project-Based Science Lessons
   a) Use real problems as starting points, such as waste management, plant growth, or local water quality.
   b) Let students design experiments, test solutions, and share results, ensuring that learning builds on what they already know.
2) Integrate Culture and Everyday Life
   a) Connect STEM to local traditions (e.g., using weaving to teach patterns, or food preparation to explain changes of matter).
   b) This makes learning authentic and helps students see science as part of their lives.
3) Strengthen Teacher Capacity
   a) Provide professional development on how to design and guide inquiry-based STEM lessons.
   b) Encourage teacher collaboration so confidence grows through shared experiences and reflection.
4) Leverage Technology Wisely
   a) Introduce digital tools and robotics as supports for inquiry, not replacements for thinking.
   b) Use apps, simulations, or AR to make invisible science concepts (like energy flow or microscopic structures) visible and understandable.

Taken together, these findings reinforce the objective outlined in the introduction: STEM fosters meaningful learning in elementary science education when inquiry, teacher readiness, cultural grounding, and technology come together. Where these conditions are absent, STEM risks becoming fragmented or superficial. Where they are present, STEM creates powerful opportunities for children to experience science as a process of discovery and meaning-making that is both joyful and enduring.

4. Conclusion

This integrative literature review examined how STEM approaches are implemented in elementary science education and how such integration supports meaningful learning. Based on an analysis of 18 peer-reviewed studies published between 2015 and 2024, the findings indicate that STEM integration can effectively promote meaningful learning when it is grounded in inquiry-based pedagogy, real-world problem solving, cultural relevance, and the purposeful use of technology. Across the reviewed studies, meaningful learning was consistently reflected in students' ability to connect scientific concepts with prior knowledge, everyday experiences, and authentic contexts, rather than relying on rote memorization.

The review shows that STEM-based learning activities enhance elementary students' problem-solving skills, critical thinking, scientific literacy, and learning motivation, particularly when learning tasks are framed around real-life issues such as environmental challenges or daily phenomena. These contexts encourage students to actively construct knowledge, test ideas, collaborate, and reflect on solutions, which are central characteristics of meaningful learning in science education. However, the findings also highlight that the success of STEM integration is strongly influenced by teacher readiness. Although teachers generally recognize the value of STEM, limited pedagogical training, insufficient confidence, and constrained instructional resources often hinder meaningful implementation, resulting in surface-level activities rather than deep conceptual understanding.

Another important implication concerns the role of cultural and contextual relevance. STEM learning becomes more meaningful when scientific concepts are embedded in students' local cultures and lived experiences, helping learners perceive science as relevant and accessible. Technology further supports meaningful learning when used as a tool to enhance inquiry, visualization, collaboration, and experimentation, rather than as an end in itself.

Despite its contributions, this study has limitations. The number of reviewed studies is relatively limited, and variations in research design and outcome measures restrict direct comparison. In addition, most studies emphasize short-term learning outcomes, leaving long-term impacts underexplored. Future research should therefore include longitudinal studies, investigate effective professional development models for teachers, and explore STEM implementation across diverse cultural and socio-economic contexts. Overall, STEM integration offers a promising pathway to meaningful learning in elementary science when pedagogical, contextual, and instructional conditions are coherently aligned.

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