INNOVATIVE PRACTICES IN STEM EDUCATION

Emerging Technologies, Pedagogies and Learning Models

Editor

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Innovative Practices in STEM Education: Emerging Technologies, Pedagogies and Learning Models

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Any paper submitted for the book chapter is reviewed by at least two international reviewers with expertise in the relevant subject area. Based on the reviewers' comments, papers are accepted, rejected, or accepted with revision. If the comments are not addressed well in the improved paper, then the paper is sent back to the authors to make further revisions. The accepted papers are formatted by the conference for publication in the proceedings.

About the Book

Innovative Practices in STEM Education: Emerging Technologies, Pedagogies and Learning Models provides a comprehensive examination of contemporary approaches that are reshaping STEM teaching and learning across diverse educational contexts. The book brings together theory-driven perspectives, empirical research, and practice-based illustrations to demonstrate how innovative pedagogies and technologies can be effectively integrated into sustainable and equitable STEM education.

The volume explores a wide range of instructional models, including problem-based and inquiry-based learning, project-based and design-based pedagogy, mathematical modelling, gamification, game-based learning, and computational thinking. These approaches are examined through robust theoretical lenses and supported by international examples, large-scale research analyses, and programmatic case studies. Particular emphasis is placed on bridging theory and practice, with concrete illustrations drawn from initiatives such as PLTW, NGSS-aligned curricula, PISA frameworks, and the Foundations in Science and Mathematics (FSM) program.

Emerging technologies constitute a central focus of the book. Chapters investigate the pedagogical potential of augmented and virtual reality, metaverse environments, open-source platforms, and online learning ecosystems in enhancing engagement, collaboration, assessment, and learning analytics. At the same time, the book critically addresses implementation challenges related to infrastructure, teacher preparation, equity, privacy, and sustainability—highlighting the need for systemic and policy-level support.

Extending beyond classroom instruction, the book also examines interdisciplinary expansions of STEM education through STEAM integration, entrepreneurship (E-STEM), community-based enrichment models, and rural STEM research initiatives. These chapters foreground creativity, innovation, identity development, and social relevance, positioning STEM education as a powerful vehicle for both individual empowerment and societal advancement.

Designed for researchers, graduate students, teacher educators, practitioners, and policymakers, this book offers a forward-looking and practice-oriented resource for those seeking to understand and implement innovative STEM education models. By synthesising emerging technologies, pedagogical innovation, and inclusive learning designs, the volume contributes to a more coherent and future-ready vision of STEM education.

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Foreword

Innovative practices in STEM education have become essential in addressing the complex educational, technological, and societal challenges of the 21st century. As scientific knowledge expands and digital technologies reshape how learning occurs, educators are increasingly called upon to design learning environments that are learner-centred, equitable, technology-enhanced, and grounded in strong theoretical foundations. This edited volume responds to that call by presenting a comprehensive exploration of how emerging pedagogies, technologies, and learning models can be translated from theory into meaningful and sustainable STEM practice.

The chapters in this book collectively demonstrate that innovation in STEM education is not driven by technology alone, but by the thoughtful integration of pedagogy, curriculum design, assessment, and contextual responsiveness. Drawing on diverse theoretical frameworks—including integrative STEM education, inquiry- and problem-based learning, variation theory, computational thinking, gamification, and TPACK—the volume illustrates how research-informed approaches can support deep conceptual understanding, creativity, collaboration, and critical thinking across STEM disciplines. Mathematics is positioned as a unifying and generative discipline, bridging science, technology, and engineering through modelling, problem solving, and abstraction.

A distinctive contribution of this book lies in its strong emphasis on implementation and equity. Through international examples, program-based case studies, and large-scale research syntheses, the chapters illuminate how innovative STEM practices are enacted across face-to-face, hybrid, and virtual learning environments. Special attention is given to inclusive pedagogies that address disparities related to access, geography, socioeconomic status, and digital infrastructure—particularly in rural, underserved, and post-pandemic contexts.

The volume also captures the evolving landscape of STEM education by engaging with emerging technologies such as augmented reality, virtual environments, metaverse applications, open-source platforms, and game-based learning. Rather than treating these tools as ends in themselves, the contributors critically examine their pedagogical affordances, assessment implications, ethical considerations, and sustainability. Complementing this technological focus, chapters on STEAM integration, entrepreneurship (E-STEM), and community-based enrichment programs broaden the scope of STEM education to include creativity, innovation, leadership, and real-world relevance.

Taken together, this book offers a timely and evidence-informed contribution to the field of STEM education. It speaks to researchers, teacher educators, practitioners, and policymakers seeking to move beyond fragmented innovations toward coherent, scalable, and equitable STEM learning ecosystems. By bridging theory and practice, the volume advances a vision of STEM education that is adaptive, inclusive, and responsive to the needs of learners and societies alike.

December 2025

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CONTENTS

Chapter 1

Teaching Methods and Applications in STEM Education: From Theory to Practice

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Chapter Highlights

This section outlines how theory-driven and innovative pedagogical approaches can be translated into sustainable STEM classroom practices, positioning mathematics as a unifying discipline across science, technology, and engineering.

- Theoretical Frameworks Bridging Theory and Practice – Draws on Integrative STEM Education, Variation Theory, Inquiry- and Context-Based Learning, and the TPACK model to demonstrate how educational theory informs effective STEM instruction.
- Innovative and Diverse Pedagogical Approaches – Examines methods such as project-based learning, inquiry-based learning, mathematical modelling, design-based pedagogy, variation theory-based instruction, and computational thinking, highlighting their roles in supporting conceptual understanding, creativity, and collaboration.
- International and Program-Based Illustrations – Presents examples from PLTW, NGSS, PISA, and case studies from the Foundations in Science and Mathematics (FSM) program at Indiana University, illustrating implementation across face-to-face and hybrid learning environments.

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Introduction

STEM education has become one of the most influential educational reform movements of the past two decades. Its growth reflects a global recognition that economic competitiveness, technological advancement, and social well-being depend on nurturing students' ability to think critically and creatively across disciplines (National Research Council, 2011; Sanders, 2012). At its core, STEM education aims to connect the traditionally separate domains of science, technology, engineering, and mathematics through meaningful, authentic learning experiences that reflect real-world practices. Yet, while the term "STEM" has become nearly universal, scholars caution that its meaning is often ambiguous and that technology and engineering are easily overshadowed unless integration is purposefully designed (Sanders, 2012). For this reason, the notion of integrative STEM education anchored in design-based, problem-solving pedagogy has emerged as a best-practice model aligned with principles of the learning sciences (Bransford et al., 2000; Sanders, 2012).

Within this integrated framework, mathematics occupies a distinctive position. Beyond serving as one of the four domains, mathematics functions as a universal language for modeling, representing, and solving problems across scientific and engineering contexts (English, 2016; Tasarib et al., 2025). Recent bibliometric analyses confirm the increasing global interest in mathematical modeling as a central connector within STEM education, emphasizing its authenticity, problem-solving potential, and the challenges it poses for teacher preparation (Fajri et al., 2025; Tasarib et al., 2025). From elementary school projects linking modeling to mathematical literacy and creativity (Fajri et al., 2025) to advanced investigations incorporating computational thinking and simulation (Tasarib et al., 2025), modeling has become an indispensable bridge between abstract mathematical concepts and applied STEM practices.

At the same time, an expanding body of research identifies innovative pedagogical approaches that enhance conceptual understanding in mathematics and STEM. Variation Theory (Marton & Pang, 2006) has been successfully adapted into structured STEM teaching frameworks (Hasan et al., 2024), enabling students to discern critical features of concepts through systematic variation and invariance. Similarly, context-based inquiry models, grounded in Science–Technology–Society (STS) perspectives and the Engineering Design Process (EDP), embed STEM learning in authentic societal problems (Sutaphan & Yuenyong, 2019). Together, these frameworks show how deliberate instructional design can foster both disciplinary depth and interdisciplinary application.

The effectiveness of STEM education, however, depends fundamentally on teachers. Despite major investments in policy and curriculum reform, many initiatives fall short because teachers are not sufficiently prepared to enact integrated pedagogies or to translate research-based strategies into classroom practice (Milner-Bolotin, 2018). Consequently, teacher education and professional development (PD) must go beyond transmitting content knowledge. They should also model innovative STEM instruction, cultivate reflective habits, and foster evidence-based decision-making and growth mindsets (Shulman, 1986; Mishra & Koehler, 2006; Milner-Bolotin, 2018). Recent international efforts, such as certificate programs in Ukraine, illustrate how interdisciplinary collaboration, project-based learning, and digital tools including augmented and virtual reality can strengthen teachers' readiness for contemporary STEM classrooms (Velychko et al., 2022).

The post-pandemic context has further heightened the urgency of these reforms. The COVID-19 crisis magnified existing inequities in access to quality STEM education and accelerated the integration of digital technologies into teaching (World Bank, 2021). Teachers were suddenly required to navigate remote and hybrid environments, adapt curricula, and sustain student engagement under unprecedented conditions. These experiences underscored the need for flexible, technology-supported, and student-centered instructional models (Velychko et al., 2022). Programs such as the Foundations in Science and Mathematics (FSM) summer program at Indiana University illustrate how graduate-student-led initiatives can function as dynamic laboratories for testing new STEM pedagogies across in-person, hybrid, and online formats providing valuable insight into the future of teacher education and practice.

The purpose of this chapter is to examine and illustrate innovative and inclusive approaches to STEM teaching, with particular attention to mathematics education and the implications of post-pandemic learning environments. Drawing upon theoretical frameworks, recent empirical research, and real-world examples, the chapter aims to provide educators and researchers with a comprehensive understanding of how mathematics can act as a bridge among STEM disciplines. It also explores the evolving professional development needs of teachers and highlights outreach initiatives such as the FSM program that can inform future practice and policy.

This chapter contributes to the broader volume Innovative Approaches in

STEM Education: Methods, Practices, and Impacts by emphasizing the often-underrepresented role of mathematics in STEM integration, situating STEM pedagogy within the realities of post-pandemic education, and illustrating how evidence-based strategies can advance both classroom instruction and teacher preparation. By combining global perspectives with localized examples, it underscores the dual necessity of theoretical clarity and practical implementation for fostering equitable and sustainable STEM education.

To guide the discussion, the central research question addressed in this chapter is:

How can mathematics education be leveraged as a bridge for meaningful STEM integration in innovative and inclusive ways, particularly considering post-pandemic teaching and learning contexts?

Theoretical Foundations of STEM Education

STEM education is grounded in a set of interrelated theoretical perspectives that emphasize integration, constructivist learning, and the centrality of teacher knowledge. One of the earliest and most influential frameworks is integrative STEM education, which Sanders (2012) defines as technological or engineering design-based learning that intentionally connects concepts and practices from science and mathematics with those of technology and engineering. This approach positions design not as an optional activity but as the pedagogical core that binds disciplines together. It aligns with the principles of the learning sciences, which highlight that meaningful learning emerges when students activate prior knowledge, engage in authentic problems, receive feedback through extended practice, and collaborate productively (Bransford et al., 2000). In this view, integrative STEM is not merely a curricular structure, but a learning philosophy grounded in design-based pedagogy.

Building on this foundation, Kelley and Knowles (2016) proposed a widely cited framework that identifies mathematics and science as anchor disciplines and positions engineering design as the "glue" connecting them. Their model emphasizes three essential components: disciplinary grounding, meaningful integration through authentic problems, and the cultivation of 21st-century skills such as collaboration and problem-solving. This framing reinforces the pivotal role of mathematics, not only as a discipline in its own right but also as a language and toolset for modeling, representing, and reasoning across STEM domains. Recent bibliometric analyses support this view, revealing that mathematical modelling has become a dominant theme in global STEM scholarship and is increasingly recognized as a bridge between abstract mathematics and real-world application (Tasarib et al., 2025; Fajri et al., 2025).

Theories of learning further shape how STEM teaching methods are designed and implemented. Variation Theory, developed by Marton and Pang (2006), offers a lens for understanding how learners discern critical aspects of a concept through experiences of variation and invariance. Hasan et al. (2024) extended this framework into a practical guide for STEM educators, demonstrating how patterns of contrast, separation, generalization, and fusion can be structured to deepen students' awareness of complex ideas. In mathematics classrooms, this approach provides a powerful means to make abstract relationships such as the interplay of slope and curvature in graphs visible and comprehensible to learners.

Another important theoretical strand comes from context-based inquiry models, particularly those influenced by Science–Technology–Society (STS) perspectives and the Engineering Design Process (EDP). Sutaphan and Yuenyong (2019) proposed a seven-stage model beginning with the identification of social issues and progressing through solution development, knowledge acquisition, prototyping, testing, and socialization. This structure demonstrates how societal relevance, design practices, and disciplinary knowledge can be interwoven into a coherent inquiry cycle. For mathematics educators, such models encourage embedding concepts in authentic contexts such as using functions to model pollution levels or geometry to optimize packaging design thereby enhancing relevance, motivation, and transfer of learning.

While these frameworks describe how students learn in integrated STEM environments, their success ultimately depends on teachers' professional knowledge. Shulman's (1986) concept of Pedagogical Content Knowledge (PCK) introduced the idea that teaching requires a unique form of expertise combining content and pedagogy. Mishra and Koehler (2006) later extended this to include technology through the Technological Pedagogical Content Knowledge (TPACK) framework. Both underscore that effective teaching involves not only knowing subject matter but also anticipating misconceptions, designing representations, and leveraging appropriate tools for learning. Milner-Bolotin (2018) stresses that evidence-based teacher education must bridge research and classroom practice by modeling innovative pedagogy, fostering reflection, and cultivating growth mindsets. Similarly, Velychkoet al. (2022) demonstrate how certificate training programs can prepare in-service teachers for interdisciplinary collaboration, project-based learning, and the integration of emerging technologies such as augmented and virtual reality.

Taken together, these theoretical perspectives demonstrate that STEM education is not defined by a single model but by a constellation of complementary frameworks. Integrative STEM emphasizes design-based connections across disciplines (Sanders, 2012); the Kelley and Knowles (2016) framework situates mathematics as a foundational anchor; Variation Theory (Hasan et al., 2024) offers a structured approach to concept development; and context-based inquiry (Sutaphan & Yuenyong, 2019) situates learning within authentic, socially relevant problems. Underpinning all of these is the recognition that teacher knowledge, preparation, and ongoing professional development are indispensable for meaningful and sustainable implementation (Milner-Bolotin, 2018; Velychko et al., 2022). Collectively, these foundations form the conceptual scaffolding for the innovative teaching methods and classroom applications explored in the following section.

Core STEM Teaching Methods

STEM education is implemented through a variety of teaching methods that translate theoretical foundations into classroom practice. These approaches share a common emphasis on inquiry, problem-solving, and interdisciplinarity, yet each provides a unique pathway for engaging students with mathematics and STEM concepts. This section discusses the major methods that have gained prominence in recent years, examining their theoretical underpinnings, practical applications, and significance across STEM disciplines.

The figure 1 illustrates the key instructional approaches explored in the chapter, showing how inquiry, modeling, design, variation, and technology integration intersect under the framework of Core STEM Methods.

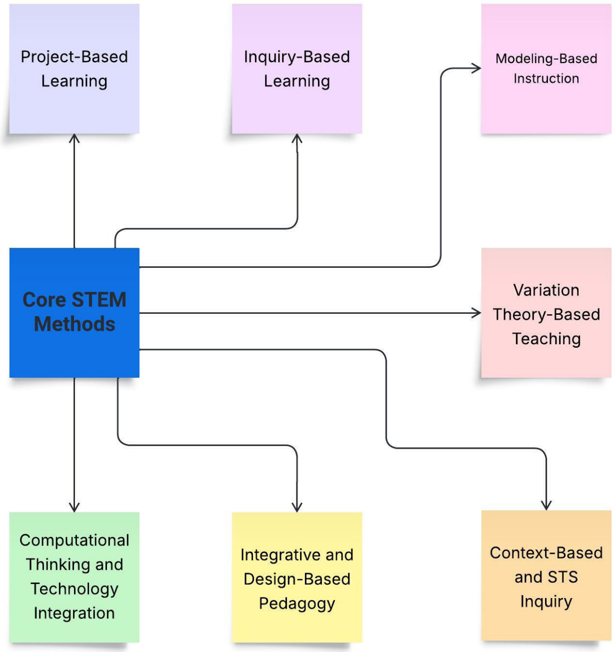

Figure 1. Core STEM Teaching Methods Examined in This Chapter

Project-Based Learning

Project-Based Learning (PBL) has long been recognized as a central approach for promoting authentic engagement in STEM education. In PBL environments, students explore complex, open-ended questions or challenges that require sustained inquiry, critical thinking, and the integration of multiple disciplines. This approach mirrors the problem-solving processes of scientists, engineers, and mathematicians in the real world. Research consistently shows that PBL enhances motivation, deepens conceptual understanding, and fosters collaboration among students (Krajcik & Blumenfeld, 2006).

Within mathematics education, PBL often takes the form of applied projects that situate mathematical concepts in meaningful contexts. Examples include analyzing the trajectory of a basketball shot through quadratic functions, designing packaging that minimizes material waste using surface area and volume calculations, or constructing statistical models to interpret community survey data. In science, projects may involve investigating renewable energy sources or testing water quality in local rivers, while in engineering and technology, students frequently engage in prototyping, iteration, and optimization tasks. These experiences encourage students to apply disciplinary knowledge while developing creativity, persistence, and collaboration.

Kelley and Knowles (2016) argue that PBL functions as a mechanism for achieving integrative STEM, positioning mathematics and science as anchor disciplines while using engineering design to structure inquiry. Through this design-oriented framework, students learn not only what to apply but also how knowledge from different fields can be combined to solve authentic problems. However, the effectiveness of PBL depends heavily on teacher scaffolding and design. Without careful planning, projects risk emphasizing superficial engagement over substantive learning. Therefore, professional development initiatives frequently highlight strategies for balancing open-ended exploration with explicit attention to disciplinary learning goals. Teachers are encouraged to integrate formative assessments, reflection checkpoints, and explicit discussion of mathematical and scientific principles throughout project cycles to ensure both rigor and relevance.

Inquiry-Based Learning

Inquiry-Based Learning (IBL) emphasizes the process of questioning, investigating, and constructing explanations, closely mirroring the authentic practices of scientists, engineers, and mathematicians. At its core, IBL engages students in evidence-based reasoning encouraging them to explore phenomena, collect data, and develop conceptual understanding through iterative inquiry cycles. Meta-analyses indicate that inquiry approaches significantly improve students' conceptual understanding, especially when supported with structured scaffolds such as guiding questions, explicit learning goals, and formative assessments (Furtak et al., 2012).

Sutaphan and Yuenyong (2019) expanded the inquiry tradition through their context-based STEM teaching model, a seven-stage process that begins with identifying a social or environmental issue and culminates in the communication of a proposed solution. For example, students might examine local air pollution, study relevant physics and chemistry principles, apply mathematical functions to model emission patterns, and then design and present a prototype of an air filtration system. This form of inquiry connects disciplinary content with real-world relevance, helping students see how abstract knowledge can be used to address authentic societal problems. As a result, learners often exhibit higher engagement, persistence, and ownership of learning.

In mathematics, inquiry-based instruction frequently involves exploring conjectures, testing hypotheses, and constructing multiple strategies for problem solving. For instance, students may investigate whether the area of all parallelograms can be derived from the same reasoning used for rectangles, thereby uncovering generalizations through exploration and reasoning. In science, inquiry manifests through experimental investigation, while in engineering, it takes the form of design and optimization challenges that demand iterative testing and revision. Across all STEM domains, IBL encourages curiosity and deep reasoning, but its success depends on careful instructional design. Effective inquiry requires teachers to balance openness with structure offering enough freedom for discovery while ensuring that core disciplinary ideas remain explicit and central to the learning process.

Modeling-Based Instruction

Mathematical modeling has become a cornerstone of integrated STEM education, serving as both a cognitive process and a pedagogical bridge across disciplines. Sanders (2012) and Kelley and Knowles (2016) emphasize that mathematics functions as the connective tissue of STEM, and modeling is the practice that makes this integration visible and actionable. Through modeling, students move fluidly between abstract representations and real-world phenomena, translating lived experiences into quantifiable relationships and testable predictions. Bibliometric studies confirm a significant rise in global research on modeling since 2015, underscoring its growing importance in STEM education and its potential to promote authentic learning (Tasarib et al., 2025; Fajri et al, 2025).

Classroom applications of modeling span all educational levels and disciplines. In elementary settings, students may use manipulatives to represent fractions through familiar contexts, such as dividing food items or allocating resources, or they may develop simple models related to financial literacy, such as budgeting or pricing scenarios. At the secondary level, modeling becomes increasingly analytical: learners can apply systems of equations to optimize production costs, employ quadratic and exponential functions to predict motion or growth, or use statistical modeling to interpret data from community-based research. In university contexts, modeling often involves computational simulations and interdisciplinary problem solving, such as developing algorithms for disease spread, fluid dynamics, or environmental forecasting. Across all levels, modeling tasks cultivate students' ability to connect mathematics with practical inquiry and to recognize the iterative nature of problem solving.

While modeling is valuable in every STEM domain, its epistemic function in mathematics is particularly significant because it links symbolic reasoning with contextualized understanding. Through the modeling process formulating a problem, mathematically representing it, analyzing and solving it, validating results, and interpreting findings students learn to see mathematics not merely as a set of procedures but as a dynamic language for sense-making. This iterative cycle allows learners to test the boundaries of abstraction and adjust their representations in light of evidence, fostering both creativity and rigor.

Despite its potential, effective implementation of modeling remains a challenge. Many teachers report limited preparation in facilitating the modeling cycle or in designing open-ended modeling tasks that extend beyond textbook-style word problems. Without sufficient support, modeling can be reduced to mechanical computation rather than authentic inquiry. Therefore, teacher professional development (PD) and curriculum design must provide structured frameworks, task exemplars, and classroom-based case studies that illustrate how modeling supports learning across STEM subjects. Future research should continue to examine how modeling can be integrated in ways that maintain mathematical depth while promoting interdisciplinary relevance. When approached as a tool for exploration and reasoning rather than routine problem solving, modeling-based instruction embodies the spirit of integrated STEM bridging abstract theory with the complexity of the real world.

Variation Theory-Based Teaching

Variation Theory provides a structured and evidence-informed approach to designing lessons that make the critical features of concepts visible to learners. According to Marton and Pang (2006), learning takes place when students discern what varies and what remains constant within a set of examples or experiences. This process enables learners to identify essential attributes of a concept rather than focusing on superficial details. Building on this foundation, Hasan et al (2024) proposed a seven-step framework for applying variation theory to STEM teaching, emphasizing systematic contrast, sequencing, and integration to guide students' conceptual understanding.

In mathematics education, variation theory can be operationalized through deliberate changes in task design. For instance, teachers may ask students to compare linear and quadratic functions that share the same slope (contrast), modify slope and intercept independently to explore their distinct effects on graphs (separation), generalize emerging patterns across different families of functions (generalization), and finally synthesize these insights to develop a comprehensive view of relationships among parameters (fusion). Through such carefully orchestrated variation, students move beyond memorization and begin to recognize mathematical structure and interconnectedness.

The same principle can extend across other STEM disciplines. In science, lessons might vary one environmental condition such as temperature or light intensity while holding others constant to reveal causal relationships. In engineering and technology, variation can be embedded in design cycles where a single parameter of a prototype (e.g., material type, gear ratio, or angle) is systematically modified to test its impact on performance. These examples demonstrate how variation theory provides a cross-disciplinary design principle that emphasizes conceptual contrast and precision.

What makes variation theory particularly powerful is its ability to support the discernment of abstract ideas a challenge frequently encountered in mathematics and related fields. By intentionally structuring experiences that reveal patterns and boundaries, teachers help students grasp the essence of complex concepts that might otherwise remain opaque. In this sense, variation theory serves not only as a pedagogical model but also as a bridge between theory and classroom practice, promoting deeper understanding through thoughtfully designed opportunities to notice what truly matters in learning.

Context-Based and STS Inquiry

Context-based inquiry methods build upon the traditions of Science–Technology–Society (STS) education and the Engineering Design Process (EDP) to embed STEM learning in authentic, socially meaningful contexts. Sutaphan and Yuenyong's (2019) seven-stage model begins with the identification of a real-world problem and progresses through solution generation, knowledge acquisition, prototyping, testing, and communication. This cyclical structure mirrors the way scientists and engineers approach real problems iteratively refining ideas through evidence, design, and reflection.

This model is particularly well suited to STEM education because it situates disciplinary content in contexts that are both culturally and socially relevant. Rather than treating mathematics, science, and engineering as isolated subjects, context-based inquiry allows students to explore how knowledge from multiple domains converges to address complex societal needs. For instance, students might design cost-effective food packaging that requires geometric reasoning and materials science, optimize local energy use through mathematical modeling and physics principles, or develop safety devices that combine statistical analysis, data visualization, and engineering design. These types of projects demonstrate how STEM learning can be both technically rigorous and socially meaningful, promoting civic engagement alongside academic growth.

Mathematics benefits directly from this approach, as it consistently serves as the analytical and justificatory tool within the inquiry cycle. Students use mathematical reasoning to quantify relationships, evaluate design trade-offs, and validate proposed solutions. In engineering and technology, the same framework aligns naturally with prototyping and iterative improvement, emphasizing the process of testing and refining ideas based on measurable data. In science, it supports inquiry through hypothesis formation, experimentation, and communication of findings. Thus, context-based inquiry provides a versatile structure for integrating STEM disciplines around problems that matter to students' lives.

However, successful implementation depends on teachers' ability to select and adapt contexts that are genuinely relevant and developmentally appropriate for their learners. When the chosen contexts resonate with students' experiences and communities, engagement deepens, and abstract concepts become more tangible. In this sense, context-based and STS inquiry not only enhance content mastery but also position STEM education as a vehicle for social awareness and purposeful problem-solving connecting classroom learning to the broader human and environmental challenges of the twenty-first century.

Integrative and Design-Based Pedagogy

Integrative STEM education, as articulated by Sanders (2012), places technological and engineering design at the heart of the learning process. In this model, learning unfolds through the act of designing, constructing, testing, and refining solutions to complex, real-world problems, with mathematics and science serving as essential tools throughout the process. Design becomes both a method of inquiry and a context for application connecting theoretical understanding with tangible outcomes and authentic decision-making.

Classroom examples illustrate the versatility of this approach. Students may construct geometric models to explore algebraic relationships, design and test bridges to apply geometric and physical principles, or program robots to integrate coding, measurement, and design logic. Through such experiences, learners engage simultaneously in mathematical reasoning, scientific experimentation, and technological creativity. Outreach programs such as the Foundations in Science and Mathematics (FSM) initiative at Indiana University demonstrate how graduate instructors employ design-based projects to help younger learners bridge mathematics and scientific inquiry. These projects not only enhance understanding but also build confidence, collaboration, and persistence skills essential for success in STEM fields.

Design-based pedagogy is particularly well suited for interdisciplinary learning because it mirrors how professionals in STEM disciplines tackle real-world challenges. It promotes innovation, collaboration, and systems thinking by encouraging students to apply multiple perspectives toward a shared goal. However, its successful implementation depends on several factors: adequate resources (materials, equipment, and lab space), teacher expertise in managing open-ended design processes, and curricular alignment that connects design tasks to core disciplinary standards. While its emphasis on authentic problem-solving makes it highly motivating, there is a risk that essential mathematics or science content may be overshadowed if design tasks are not carefully scaffolded. For this reason, teacher professional development (PD) plays a crucial role in ensuring that design-based learning maintains a balance between creative exploration and disciplinary rigor.

When thoughtfully supported, integrative and design-based pedagogy exemplifies the spirit of STEM education bridging theory with practice, fostering curiosity, and empowering students to become innovators and problem solvers in both academic and real-world contexts.

Computational Thinking and Technology Integration

The rapid expansion of digital technologies has profoundly transformed STEM pedagogy. Computational thinking (CT) the ability to formulate and represent problems in ways that can be solved by computers has been described as a new literacy for the 21st century (Wing, 2006). Coding, robotics, and simulations not only enhance problem-solving but also offer concrete ways for students to connect mathematics with engineering, science, and technology (Tasarib et al., 2025). Through these tools, learners begin to view computation not as a separate discipline but as an essential lens for modeling, analyzing, and creating within STEM contexts.

Classroom applications of computational thinking are wide-ranging.

Students might use programming to model geometric transformations, simulate ecosystems, or automate aspects of the engineering design process. In mathematics, CT fosters algorithmic reasoning and recursive thinking; in science, it enables the analysis of large datasets and the visualization of experimental outcomes; in engineering, it supports prototyping, simulation, and systems optimization; and in technology, it drives innovation through automation, coding, and design. Across these domains, computational thinking cultivates logical reasoning, precision, and creativity core habits of mind in STEM.

However, effective technology integration is not achieved simply by introducing new tools into classrooms. The Technological Pedagogical Content Knowledge (TPACK) framework, developed by Mishra and Koehler (2006), offers a comprehensive model for understanding the interplay among teachers' knowledge of content, pedagogy, and technology. It builds upon Shulman's (1986) concept of Pedagogical Content Knowledge (PCK) and expands it to include technological fluency as a critical dimension of teaching expertise. The framework's key components can be summarized as follows:

Content Knowledge (CK): Understanding the subject matter itself (e.g., mathematical functions, scientific concepts, or engineering principles).

Pedagogical Knowledge (PK): Knowledge of teaching methods, learning processes, assessment, and classroom management.

Technological Knowledge (TK): Understanding digital tools and their affordances, ranging from graphing software and coding platforms to AR/VR environments and simulations.

At the intersections of these domains, additional composite forms of knowledge emerge:

PCK (Pedagogical Content Knowledge): Knowing how to represent disciplinary ideas in ways that are understandable and accessible to learners (Shulman, 1986).

TCK (Technological Content Knowledge): Understanding how technology reshapes or extends disciplinary understanding for instance, using dynamic graphing tools to visualize families of mathematical functions.

TPK (Technological Pedagogical Knowledge): Recognizing how technology can modify instructional strategies, such as employing simulations to scaffold inquiry or using digital platforms for formative assessment.

TPACK (Full Integration): The convergence of content, pedagogy, and technology into balanced, student-centered learning experiences that promote deep understanding and engagement.

In practice, TPACK implies that teachers must move beyond using digital tools for novelty or engagement alone. Instead, technologies should be strategically aligned with learning objectives to enhance disciplinary understanding. For example, a simulation of projectile motion should not merely entertain students but should help them connect quadratic functions with physics principles within an inquiry cycle. Likewise, programming a robot to follow a path is most effective when embedded in lessons about geometric reasoning, measurement, and iterative design. These purposeful alignments transform technology from a passive medium into an active scaffold for conceptual development.

Professional development programs increasingly emphasize TPACK as a guiding framework for lesson design and reflection. Velychko et al. (2022) reported certificate programs that trained educators in AR/VR, robotics, and simulation-based teaching, highlighting how such technologies can support not replace conceptual learning. This emphasis has become even more critical in post-pandemic education, where teachers must integrate digital and face-to-face modalities fluidly while maintaining pedagogical coherence.

Ultimately, computational thinking and technology integration illustrate that innovation in STEM education is not merely about adopting the newest tools but about cultivating teacher expertise at the intersection of what to teach (content), how to teach it (pedagogy), and which tools best support learning (technology). The TPACK framework provides a practical and conceptual roadmap for navigating this intersection, ensuring that technology enriches rather than distracts from meaningful and equitable STEM learning.

Summary and Synthesis of Core Methods

Together, these methods, Project-Based Learning (PBL), Inquiry-Based Learning (IBL), Mathematical Modelling, Variation Theory, Context-Based Inquiry, Design-Based Pedagogy, and Computational Thinking form the practical repertoire of innovative STEM instruction. Each method brings distinct strengths: PBL and inquiry promote student-driven exploration and autonomy; modelling and variation theory strengthen conceptual understanding and mathematical reasoning; context-based and design-based approaches connect learning to social relevance and authentic problem-solving; and computational thinking expands the technological and analytical dimensions of STEM learning.

In classroom practice, these methods have been implemented across diverse educational systems and levels. Project-Based Learning (PBL) has been widely adopted in U.S. middle and high schools through initiatives such as Project Lead the Way (PLTW), where students engage in engineering and biomedical design projects requiring the application of mathematics and science concepts. In mathematics classrooms, PBL tasks often include designing a school garden to optimize area and perimeter or analyzing sports statistics to build predictive models activities that connect abstract knowledge with concrete experiences.

Inquiry-Based Learning (IBL) underpins many modern science curricula, including the Next Generation Science Standards (NGSS) in the United States, which emphasize practices of questioning, investigating, and reasoning from evidence. Mathematics educators have adapted inquiry principles by encouraging students to generate conjectures and test them for instance, exploring patterns in number theory or using dynamic software to examine properties of geometric figures.

Modelling-based instruction has become a global standard, with international assessments such as PISA defining mathematical literacy in terms of students' ability to formulate, employ, and interpret models in real-world contexts. Many European countries, including Germany and the Netherlands, have embedded modelling tasks into secondary curricula, challenging students to apply mathematics to authentic scenarios such as traffic flow, environmental sustainability, or population growth.

Variation Theory has had influence in East Asian contexts. In Hong Kong and mainland China, lesson study traditions often draw on variation theory principles, with teachers designing sequences of tasks that emphasize key contrasts and invariants (Marton & Pang, 2006). Such designs have been shown to deepen understanding by making subtle conceptual differences visible for example, varying coefficients and constants in algebraic equations to clarify their respective roles.

Context-based and STS inquiry approaches have shaped curriculum reforms in countries such as Thailand and Singapore, where STEM lessons are explicitly tied to cultural and societal issues (Sutaphan & Yuenyong, 2019). Students may design energy-saving devices for their communities or explore the chemistry of local foods, integrating disciplinary knowledge with everyday life and community impact. These approaches highlight how STEM education can foster both intellectual growth and civic responsibility.

Integrative and design-based pedagogy is central to engineering-focused curricula such as PLTW and the Engineering by Design framework of ITEEA. Students learn by designing, constructing, and evaluating prototypes that require the coordination of mathematical, scientific, and technical reasoning. In mathematics classrooms, design-based tasks may include constructing physical models to explore geometric properties or using 3D printing to visualize algebraic functions as tangible forms. Such tasks embody the creative synthesis of theory and practice.

Finally, Computational Thinking (CT) has emerged as a cross-disciplinary competency. Initiatives such as the U.S. Computer Science for All program and similar reforms across Europe and Asia integrate CT throughout K–12 education not only in computer science, but also in mathematics and science classes. Students might write code to simulate projectile motion, use spreadsheets to analyze statistical data, or program robots that apply measurement and proportional reasoning. These activities cultivate algorithmic thinking, precision, and creativity while expanding students' capacity to connect computation with conceptual reasoning.

Although each method contributes uniquely to STEM education, their impact varies by discipline. Modelling and variation theory are particularly powerful for mathematics; design-based pedagogy thrives in engineering and technology-rich environments; inquiry-based learning is central to science; and computational thinking cuts across all fields. Importantly, the most effective curricula integrate multiple approaches rather than relying on a single method. Programs such as NGSS, PLTW, and PISA all demonstrate that blended models where inquiry, modelling, design, and technology intersect are most effective for preparing students to navigate complex, interdisciplinary problems. The task for educators, therefore, is not to select one method over another but to orchestrate these approaches into coherent, balanced learning experiences that sustain engagement while maintaining disciplinary depth and rigor.

Classroom Applications and Case Studies

The practical value of STEM education becomes most visible in the classroom, where abstract frameworks are transformed into student-centered, inquiry-driven learning experiences. Across diverse educational contexts, teachers and program designers have adapted innovative approaches such as inquiry, modelling, and design-based pedagogy into projects that nurture both disciplinary depth and interdisciplinary thinking. These applications reveal how theory can be meaningfully translated into practice to engage learners in authentic, problem-solving environments.

A widely documented example is the use of context-based inquiry cycles in science and mathematics classes. Sutaphan and Yuenyong (2019) demonstrated how secondary students in Thailand engaged with local cultural and environmental issues through a seven-stage STEM framework. Projects included designing communication devices for space exploration and creating technological models based on electromagnetism. In each case, students drew upon mathematics and science knowledge to refine prototypes, test solutions, and communicate results. These examples illustrate how embedding mathematics within socially meaningful contexts can enhance relevance, promote critical thinking, and strengthen students' sense of purpose in learning.

Variation theory-based lesson designs also highlight the adaptability of innovative teaching methods. Hasan, Khan, and Ahmed (2024) described how systematically varying mathematical features such as comparing linear and quadratic functions or manipulating slope and intercept in targeted sequences helped students discern key conceptual differences. In classroom studies, students who experienced variation-based lessons consistently outperformed those in traditional settings, suggesting that careful orchestration of contrast, separation, and generalization can significantly deepen conceptual understanding.

Mathematical modelling projects offer another powerful vehicle for integrating STEM disciplines. Bibliometric research shows that modelling has been increasingly implemented across educational levels, from elementary tasks involving fractions and proportional reasoning to advanced simulations in physics and biology (Tasarib et al., 2025; Fajri et al., 2025). For example, elementary students have explored financial literacy and ethnomathematical contexts to reason proportionally, while secondary students have applied calculus to epidemic modelling and data-based prediction. These activities position mathematics not as a set of abstract computations but as a dynamic tool for interpreting and solving real-world problems.

Teacher professional development (PD) programs also illustrate how innovative pedagogies can be translated into classroom-ready practices. In Ukraine, Velychko et al. (2022) documented certificate courses that trained teachers to design interdisciplinary projects using digital platforms such as PhET simulations, Minecraft Education Edition, and robotics kits. Classroom applications included integrating geometry and physics through architectural design or combining algebra and art in explorations of quadrilaterals. These experiences demonstrate how STEM instruction can cross disciplinary boundaries while maintaining mathematical rigor and creativity.

The Foundations in Science and Mathematics (FSM) summer program provides another illustrative case of how graduate-student-led initiatives can adapt innovative pedagogies to flexible and inclusive learning environments. Courses within FSM emphasize problem-based projects, inquiry-oriented instruction, and digital tool integration. For example, in mathematics courses, students explore geometric transformations using dynamic software, analyze statistical data from real-world sources, and simulate projectile motion as part of physics mathematics integration tasks. During the COVID-19 pandemic, FSM successfully transitioned these projects to online and hybrid formats, showcasing how design-based pedagogy and modelling approaches can thrive even under disrupted conditions.

Taken together, these classroom cases underscore the adaptability and transformative potential of STEM teaching methods across grade levels, cultural contexts, and instructional modalities. Whether through inquiry projects rooted in community issues, variation-based mathematics lessons, modelling tasks that link classroom learning to authentic applications, or interdisciplinary designs enhanced by technology, innovative pedagogies provide multiple pathways to make STEM learning meaningful, equitable, and inclusive.

Challenges and Barriers in Implementing STEM Teaching

While innovative methods in STEM education offer tremendous promise, their classroom implementation continues to face a range of persistent challenges. These difficulties extend across curricular integration, assessment, teacher preparation, equity, and student motivation, and must be addressed if STEM reforms are to achieve lasting impact and scale.

A primary challenge lies in the integration of disciplines. Although frameworks such as integrative STEM and context-based inquiry provide conceptual guidance, many teachers struggle to weave mathematics, science, engineering, and technology into coherent, mutually reinforcing lessons (Sanders, 2012; Sutaphan & Yuenyong, 2019). School curricula are typically organized by rigid subject boundaries, leaving little flexibility for interdisciplinary projects or cross-department collaboration. Teachers often face a tension between covering mandated content and fostering authentic, inquiry-driven learning experiences. This structural constraint can limit innovation, even among educators who are enthusiastic about

STEM integration.

A second and closely related challenge concerns assessment and evaluation. Project-based and inquiry-oriented tasks generate rich learning opportunities, but they do not lend themselves easily to traditional testing formats. Teachers must develop rubrics that capture a range of competencies content mastery, collaboration, creativity, reasoning, and problem-solving. Hasan et al. (2024) observed that variation theory-based instruction enhances conceptual understanding, yet measuring such depth requires nuanced assessment tools that go beyond rote recall. Likewise, mathematical modelling tasks provide authentic reasoning opportunities but are notoriously difficult to evaluate consistently (Tasarib et al., 2025). Without supportive and flexible assessment frameworks, teachers may hesitate to adopt or sustain these pedagogical innovations.

Teacher preparation and professional development represent another major barrier. As Milner-Bolotin (2018) emphasizes, many reform efforts falter because teachers are insufficiently prepared to implement evidence-based approaches or to connect research with day-to-day practice. Velychko et al. (2022) further note that many teachers lack interdisciplinary fluency and hands-on experience with digital tools, highlighting the need for systematic professional learning programs that integrate theory with design-based application. Without adequate preparation and ongoing support, even motivated teachers may revert to familiar, lecture-centered practices.

Equity and access also remain pressing concerns. The COVID-19 pandemic made visible the deep disparities in digital infrastructure, teacher capacity, and student resources (World Bank, 2021). Schools in rural or under-resourced areas often face greater challenges in implementing technology-rich approaches such as computational thinking, coding, or virtual simulations. These inequities risk creating a two-tiered educational system in which some learners gain access to integrated, technology-enhanced STEM experiences while others remain confined to traditional instruction. Achieving equity therefore requires not only investment in hardware and connectivity but also culturally relevant curriculum design and sustained policy commitment to ensure that all students can participate meaningfully in STEM learning.

Finally, maintaining student motivation and engagement is an enduring challenge. Although inquiry and design projects often inspire enthusiasm, they also demand persistence, collaboration, and critical reflection skills that not all students possess or develop easily. Teachers must find a delicate balance between providing structure and allowing autonomy so that learners remain productively engaged without becoming overwhelmed. This balance is especially important in mathematics, where anxiety and disengagement are well-documented obstacles to learning (English, 2016). Without intentional scaffolding, students may view STEM projects as overly complex rather than empowering opportunities for exploration.

In summary, the challenges of implementing STEM teaching underscore the complexity of educational change. Integration across disciplines, assessment innovation, teacher development, equity, and motivation are interdependent dimensions that require coordinated action at policy, institutional, and classroom levels. Acknowledging these challenges does not diminish the promise of STEM innovation; rather, it highlights the urgent need for systemic supports that make ambitious pedagogies both feasible and sustainable in real-world classrooms.

Post-Pandemic Transformations and Lessons Learned

The COVID-19 pandemic disrupted education on a global scale, forcing an unprecedented and rapid shift to online and hybrid teaching formats. For STEM education, this transformation brought both profound challenges and unexpected opportunities. Although widespread learning losses were reported particularly in mathematics (World Bank, 2021) the crisis also accelerated the adoption of digital tools and revealed the potential of technology to reshape teaching and learning practices.

One of the most significant changes was the expansion of online and hybrid learning environments. Teachers who had little prior experience with virtual instruction suddenly had to master videoconferencing platforms, digital whiteboards, and online assessment tools. While this transition was often uneven, it demonstrated that STEM pedagogy could adapt to multiple modalities. Velychko et al. (2022) observed that professional development programs began to incorporate online simulations, robotics kits, and virtual reality applications, offering teachers new strategies for project-based and inquiry-driven learning. These tools not only supported instruction during school closures but continue to enhance in-person classrooms by providing flexible, interactive ways to explore mathematical and scientific ideas.

The pandemic also redefined teachers' professional roles. No longer serving merely as content deliverers, teachers became facilitators, technology navigators, and community connectors. Milner-Bolotin (2018) underscored the importance of cultivating reflective and research-informed practices in teacher education; the pandemic brought this to life by demanding resilience, creativity, and adaptability from educators in real time. In mathematics classrooms, for instance, teachers leveraged dynamic graphing tools, coding environments, and collaborative problem-solving platforms to sustain engagement despite physical distance.

At the same time, the crisis amplified existing inequities in STEM education. Students from under-resourced schools often lacked reliable internet access or personal devices, severely limiting their ability to participate in remote learning (World Bank, 2021). These disparities mirrored and, in some cases, widened long-standing achievement gaps. Addressing these inequities requires not only systemic investment in digital infrastructure but also a commitment to developing inclusive and culturally responsive curricula that remain accessible across diverse contexts.

Programs such as the Foundations in Science and Mathematics (FSM) summer program exemplify how STEM initiatives can adapt to these new realities. During the pandemic, FSM transitioned its mathematics and science courses into hybrid and fully online formats. Instructors integrated digital simulations, collaborative virtual projects, and discussion-based sessions, turning challenges into opportunities for innovation. For example, FSM mathematics students used platforms such as Desmos and GeoGebra to investigate geometric transformations and modelling tasks, enabling real-time visualization and interaction. These adaptations demonstrated that project-based and inquiry-driven approaches can thrive in virtual settings when instruction is carefully scaffolded and intentionally designed.

Looking ahead, the post-pandemic landscape underscores that flexibility and technological fluency will remain essential features of effective STEM teaching. Hybrid models that blend face-to-face collaboration with digital learning environments are likely to become a permanent fixture in education. Consequently, teacher preparation and professional development must emphasize not only disciplinary integration but also the purposeful use of technology. As Mishra and Koehler's (2006) TPACK framework reminds us, meaningful integration occurs at the intersection of content, pedagogy, and technology. The pandemic experience made this intersection unavoidable reinforcing that future STEM instruction must prepare students to navigate both digital and physical problem-solving spaces.

Future Directions and Recommendations

The expanding body of STEM education research shows that its success depends not only on creating innovative methods but also on building the systems that sustain them. Looking ahead, several key directions can guide the next phase of progress in both research and practice.

A priority is the central role of mathematics and modelling in integrative STEM. Bibliometric studies confirm that mathematical modelling increasingly serves as the connective practice linking abstract reasoning to authentic problem-solving (Tasarib et al., 2025; Fajri et al., 2025). Future curricula should highlight modelling cycles that invite students to move fluidly between conceptual understanding, symbolic representation, and applied contexts. When designed this way, modelling strengthens mathematical literacy while also cultivating creativity, logical reasoning, and critical thinking.

A second direction concerns the integration of emerging technologies. Computational thinking, coding, robotics, and simulations are already reshaping STEM classrooms, yet the next wave of innovation will involve artificial intelligence, data science, and immersive environments such as augmented and virtual reality. These tools extend the range of problems students can explore and mirror the technologies transforming modern research and industry (Wing, 2006; Velychko et al., 2022). To use them effectively, teacher education programs must ensure that educators apply digital tools purposefully aligning them with pedagogy and learning outcomes rather than treating them as add-ons.

The future of STEM reform also relies on a deeper commitment to teacher education and professional learning. Milner-Bolotin (2018) noted that reforms often falter when teachers are not equipped to translate evidence-based pedagogy into classroom practice. Expanding certificate programs, collaborative learning networks, and practice-based professional development (PD) is therefore essential. Effective PD should model innovative teaching approaches, provide hands-on opportunities for designing interdisciplinary lessons, and encourage reflective habits that sustain lifelong learning. Supporting teachers also means valuing their time, providing resources, and creating professional communities that empower experimentation and growth.

Equity and inclusivity must remain guiding principles for all future work. The pandemic exposed deep disparities in digital access and instructional support (World Bank, 2021). Future STEM initiatives must not only ensure equitable infrastructure but also promote culturally relevant and inclusive pedagogies. This involves designing modelling and inquiry tasks that connect with students' lived experiences, integrating ethnomathematical perspectives, and ensuring that underrepresented groups see themselves represented in STEM disciplines. Addressing gender equity, rural–urban divides, and linguistic diversity will be crucial if STEM education is to prepare all learners for participation in a global, knowledge-based society.

Finally, community-based programs such as the Foundations in Science and Mathematics (FSM) demonstrate how flexible, university–school partnerships can foster innovation. FSM's model built on graduate instructors, problem-based learning, and hybrid delivery provides a blueprint for scaling STEM opportunities while maintaining contextual relevance. Expanding such partnerships across local and national contexts could help bridge the gap between research, teacher preparation, and classroom practice.

In light of these trends, one overarching recommendation stands out: STEM education must evolve from isolated innovations to systemic, sustainable integration that connects pedagogy, technology, and teacher development. Future research should continue to investigate how specific methods such as variation theory, context-based inquiry, modelling, and design-based pedagogy enhance learning across diverse contexts. Policymakers must invest in teacher professional growth and equitable infrastructure, while educators cultivate reflective and adaptive classroom practices. Through coordinated efforts across these levels, STEM education can equip future generations with the knowledge and creativity to address the complex challenges of an interconnected world.

Conclusion

This chapter has explored the theoretical foundations, core teaching methods, classroom applications, and challenges of STEM education, with particular attention to mathematics and the evolving realities of post-pandemic teaching. Across the literature, a clear and consistent message emerges innovative pedagogical approaches such as variation theory, context-based inquiry, project-based learning, and mathematical modelling have the potential to transform classrooms by making learning more authentic, inclusive, and engaging. When these methods are integrated with computational thinking and design-based pedagogy, students are better able to connect disciplinary knowledge to real-world contexts, deepening their understanding and fostering the critical thinking, creativity, and collaboration skills essential for the 21st century.

A central theme throughout this discussion is the unique role of mathematics as a bridge across STEM disciplines. From early activities that develop modelling and problem-solving competencies to advanced projects involving functions, simulations, and data analysis, mathematics serves as the language that unites science, engineering, and technology. Recent bibliometric evidence confirms the global expansion of mathematical modelling in STEM education (Tasarib et al., 2025; Fajri et al., 2025), underscoring both the promise of this approach and the need for deeper teacher preparation. Positioning mathematics at the core of integrative STEM ensures that learners go beyond procedural proficiency to develop the capacity to represent, analyze, and solve complex, interdisciplinary problems.

The chapter has also emphasized the pivotal role of teacher preparation and professional development. Research consistently shows that STEM reforms struggle when teachers are not equipped with the necessary knowledge, resources, and confidence to implement innovative pedagogy (Milner-Bolotin, 2018; Velychko et al., 2022). Sustained professional development that blends theoretical insight with hands-on design work, collaborative reflection, and purposeful technology use is therefore essential. Programs such as the Foundations in Science and Mathematics (FSM) offer valuable models, demonstrating how graduate instructors and schools can collaborate to create flexible, project-based learning environments. FSM’s adaptation during the COVID-19 pandemic further illustrates that innovation can thrive even under challenging circumstances when guided by thoughtful pedagogy.

The challenges of implementation including curricular integration, assessment, equity, and student motivation remain significant, yet they also present opportunities for growth. The difficulty of assessing inquiry and modelling tasks invites the development of evaluation frameworks that capture conceptual understanding and creativity. The inequities exposed during the pandemic highlight the urgency of equitable infrastructure and culturally responsive teaching. Similarly, the struggle to sustain student motivation calls for a balance between guidance and autonomy so that projects remain engaging without overwhelming learners.

Looking to the future, systemic integration will be key to sustaining progress. Policymakers, researchers, and practitioners must work together to align curriculum, assessment, teacher education, and technology. Artificial intelligence, data science, and immersive technologies such as augmented and virtual reality will continue to broaden the landscape of STEM learning, but their potential will only be realized when teachers are empowered to use them purposefully. At the same time, inclusivity and equity must remain guiding principles to ensure that innovation benefits all learners, not just those with access to resources.

In summary, STEM education stands at a critical moment. The theoretical and practical advances of the past decade accelerated by the disruptions of the pandemic have laid the groundwork for more integrative, inquiry-driven, and technology-rich pedagogy. The challenge now is to scale these innovations in ways that are sustainable, equitable, and grounded in evidence-based practice. By leveraging mathematics as a unifying discipline, empowering teachers as reflective practitioners, and embracing the opportunities afforded by emerging technologies, STEM education can prepare students not only for academic success but also for active participation in an increasingly complex, interconnected world.

References

Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (2000). How people learn: Brain, mind, experience, and school (Expanded ed.). National Academy Press.

English, L. D. (2016). STEM education K–12: Perspectives on integration. International Journal of STEM Education, 3(1), 3. https://doi.org/10.1186/s40594-016-0036-1

Fajri, H. M., Marini, A., & Suyono. (2025). A bibliometric study on mathematical modelling in elementary schools in the Scopus database between 1990–2024. EURASIA Journal of Mathematics, Science and Technology Education, 21(2), em2577. https://doi.org/10.29333/ejmste/15916

Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. Review of Educational Research, 82(3), 300–329. https://doi.org/10.3102/0034654312457206

Hasan, M., Khan, R., & Ahmed, F. (2024). Application of variation theory in STEM education: A comprehensive guideline for STEM teachers. MethodsX, 12, 102500. https://doi.org/10.1016/j.mex.2024.102500

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. International Journal of STEM Education, 3(1), 11. https://doi.org/10.1186/s40594-016-0046-z

Krajcik, J. S., & Blumenfeld, P. C. (2006). Project-based learning. In R. K. Sawyer (Ed.), The Cambridge handbook of the learning sciences (pp. 317–334). Cambridge University Press. https://doi.org/10.1017/CBO9780511816833.020

Marton, F., & Pang, M. F. (2006). On some necessary conditions of learning. The Journal of the Learning Sciences, 15(2), 193–220. https://doi.org/10.1207/s15327809jls1502_2

Milner-Bolotin, M. (2018). Evidence-based research in STEM teacher education: From theory to practice. Frontiers in Education, 3, 92. https://doi.org/10.3389/feduc.2018.00092

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. Teachers College Record, 108(6), 1017–1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x

National Research Council. (2011). Successful K–12 STEM education: Identifying effective approaches in science, technology, engineering, and mathematics. National Academies Press. https://doi.org/10.17226/13158

Sanders, M. (2012). Integrative STEM education as "best practice." In H. Middleton (Ed.), Explorations of best practice in technology, design & engineering education: Volume two (pp. 103–117). Griffith University, Griffith Institute for Educational Research.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. Educational Researcher, 15(2), 4–14. https://doi.org/10.3102/0013189X015002004

Sutaphan, S., & Yuenyong, C. (2019). STEM education teaching approach: Inquiry from the context based. Journal of Physics: Conference Series, 1340, 012003. https://doi.org/10.1088/1742-6596/1340/1/012003

Tasarib, A., Rosli, R., & Rambely, A. S. (2025). Exploring the implementation of STEM education through mathematical modelling activities in schools: A bibliometric analysis. LUMAT: International Journal of Math, Science and Technology Education, 12(4), 17. https://doi.org/10.31129/LUMAT.12.4.2444

Velychko, V. E., Kaydan, N. V., Fedorenko, O. G., & Kaydan, V. P. (2022). Training of practicing teachers for the application of STEM education. Journal of Physics: Conference Series, 2288, 012033. https://doi.org/10.1088/1742-6596/2288/1/012033

Wing, J. M. (2006). Computational thinking. Communications of the ACM, 49(3), 33–35. https://doi.org/10.1145/1118178.1118215

World Bank. (2021). The state of the global education crisis: A path to recovery. World Bank, UNESCO, & UNICEF. https://doi.org/10.1596/36653

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Chapter 2

Problem-Based Learning and Inquiry-Based STEM Education

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Chapter Highlights

Effective STEM education requires equipping learners with the necessary skills to navigate the increasingly complex and technology-driven world. Among many promising pedagogical approaches, problem-based learning (PBL) and inquiry-based learning (IBL) stand as particularly promising due to their unique characteristics: Both approaches prioritize the learner being at the center of the learning process. Learners actively participate in the learning process by employing critical thinking skills through investigation. Consequently, both methods foster critical thinking skills, collaboration, and active participation of learners in authentic learning contexts, which are also essential skills for effective STEM education.

- Key Components of Problem-based Learning – The foundation of problem-based learning, characteristics, teacher roles and student benefits.
- Problem-based STEM Education– The intersection of problem-based learning and STEM, affordances of problem-based STEM education and different approaches for problem-based STEM teaching.
- Key Components of Inquiry-based Learning – The foundation of inquiry-based learning, characteristics.
- Inquiry-based STEM Education – The intersection of inquiry-based learning and STEM, affordances of inquiry-based STEM education and different approaches for inquiry-based STEM teaching.

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Introduction

Problem-based learning (PBL) is grounded in the principles of constructivism. (El Sayary et al., 2015; Mabley et al., 2020; Hmelo-Silver, 2004; Thibaut et al., 2018). Constructivism is predicated on the notion that learners should be encouraged to construct their own understanding and establish meaningful connections between new concepts and prior experiences. In this sense, the PBL approach aligns with constructivist learning theories (Thibaut et al., 2018; Woods-McConney et al., 2020). PBL involves students to collaborate in small groups and acquire the necessary knowledge to resolve a problem (Hmelo-Silver, 2004). Originated in medical education, PBL was pioneered in the School of Medicine at McMaster in the 1960s (de Graaff & Kolmos, 2003; Mabley et al., 2020; Servant-Miklos, 2018). Smith et al. (2022) characterized four principles of PBL as:

Problems embed in rich and relevant learning contexts;
active and strategic metacognitive reasoning;
collaboration based on intrinsic motivation;
problems embedded in real and rich contexts.

The effectiveness of PBL depends on the problems being placed in rich, relevant and authentic settings that allow students to grow in their ability to apply resources, knowledge, and skills both inside and outside of their discipline (Smith et al., 2022). Moreover, the problems need to be complex and ill-structured that are moderately scaffolded and situated in authentic contexts, as such problems both engage and challenge learners while enabling them to connect prior knowledge with cognitive development (Jonassen & Hung, 2008). In this manner, students' active involvement in the process of problem solving become central. Thus, PBL approach is accepted as student-centered pedagogy (El Sayary et al., 2015).

Recognized as a student-centered pedagogy, the effective implementation of the PBL approach in classroom contexts carries significant importance. Several models describing its application are discussed in the literature, one notable example being the seven-step model proposed by de Graaff and Kolmos (2003) (see Figure 1). This model starts with clarifying concepts being addressed during PBL process and finishes with testing and reporting the solution step.

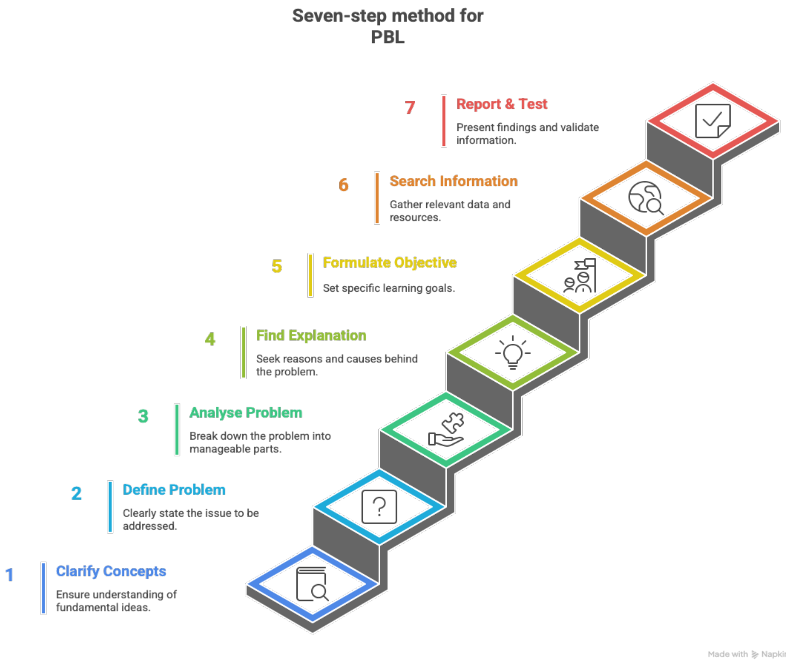

Figure 1. Seven-step model for using PBL in the classrooms (Adapted from de Graaff & Kolmos, 2003)

Teachers' role in PBL

While students actively involved in solving real world problems (Hung et al., 2008), teachers' roles are suited in being a guide and facilitator for students to develop appropriate problem-solving skills (de Graaff & Kolmos, 2003; El Sayary et al., 2015; Smith, 2022). It is important to maintain a careful balance in the level of guidance provided. While they provide required support for students to solve problems by acquiring new knowledge and skills, they also need to provide space for their student to become independent learners (Slough & Milam, 2013).

Affordances of PBL

PBL approach is implemented across diverse educational settings, ranging from primary to undergraduate education (Hung et al., 2008; El-Sayary et al., 2015; Taylor & Mifflin, 2008; Rehmat & Hartley, 2020; Yew & Goh, 2016). It has positive outcomes on developing skills including problem-solving, critical thinking, higher order thinking, collaborative learning, research and negotiation skills as well as communication and teamworking skills. In addition, the approach nurtures learners' self-confidence and motivation. Lastly, there has been significant improvements in students' performances in various tasks significantly (de Graaff & Kolmos, 2003; Hung et al., 2008; Kilroy, 2004; Warnock & Mohammadi-Aragh, 2015; Wood, 2004; Yew & Goh, 2016). Consequently, PBL is associated with three types of learning: cognitive, content and collaborative learning (de Graaff & Kolmos, 2003).

Problem-based STEM Education

PBL approach is usually associated with interdisciplinarity (Sayary, 2006). Interdisciplinarity, which entails the integration of knowledge, skills, and perspectives from two or more disciplines to generate products, account for phenomena, or address problems in ways unattainable within the boundaries of a single discipline (Boix Mansilla, 2010), the PBL approach offers a rich and meaningful context for exploring the interdisciplinary nature of STEM. By engaging learners in authentic, ill-structured problems that demand cross-disciplinary reasoning, PBL creates opportunities for students to transcend disciplinary silos, synthesize diverse forms of knowledge, and cultivate practices of inquiry that mirror those employed in real-world scientific and technological endeavors. Thus, the PBL framework highlights the potential of STEM education to advance both theoretical understandings of interdisciplinarity and its practical realization in classroom settings. Indeed, Asghar et al. (2012) identified PBL as the best strategy to teach STEM.

El Sayary et al. (2015) explained how PBL's three types of knowledge (content, collaborative and cognitive) which led to higher order thinking skills are situated in problem-based STEM education (see, Figure 2). Through problem-based STEM education, students could develop higher order thinking skills.

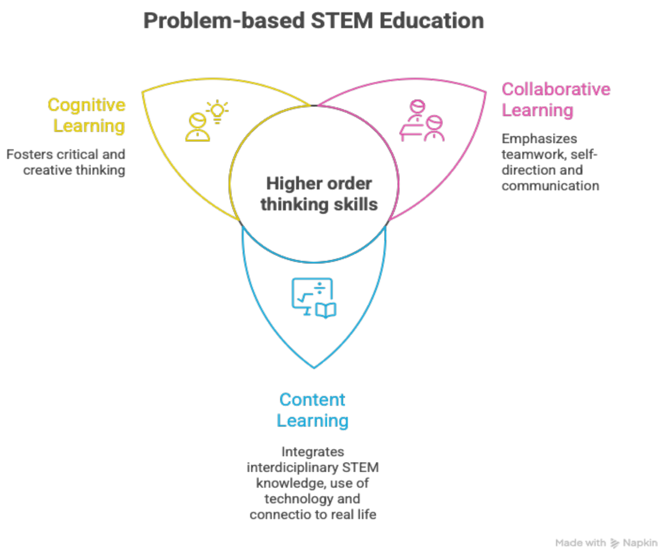

Figure 2. Problem-based STEM education (Adapted from El Sayary et al., 2015)

Affordances of problem-based STEM education

The literature increasingly documents positive outcomes associated with problem-based STEM education. Figure 2 illustrates how problem-based STEM education can be a valuable approach to enhance students' multiple skills development, including higher order thinking skills, 21st century skills (problem solving, collaboration, technology use, productivity, STEM awareness), as well as improving performances in STEM subjects and inspiring interest in STEM careers. Boosting students' motivation, engagement, enthusiasm and encouraging team work and communication were other benefits reported in the literature (Anazifa & Djukri, 2017; Beier et al., 2018; Coufal, 2022; de Graaff & Kolmos, 2003; Karamustafaoglu & Pektas, 2023; Rehmat & Hartley, 2020; Smith et al., 2022; Thibaut et al., 2018).

Approaches for problem-based STEM teaching sequences

While PBL approach is frequently adopted in educational settings, problem-based STEM applications are relatively new (Cebesoy, 2023). As there are many benefits that are associated with using problem-based STEM education, researchers used various methods to integrate PBL to STEM (e.g., Abbott, 2016; Karamustafaoglu & Pektas, 2023; Sarı et al., 2018; Rahmat & Hartley, 2020). For instance, Sari and colleagues (2018) used a five-step model to integrate PBL into STEM (Figure 3). In their model, teaching sequence started with identifying the problem to be addressed (step 1). The students, then, collected information and resources required to solve the problem (Step 2). In step 3, students formed hypothesis and suggested solutions to the problem being addressed. The students discussed possible solutions and selected the one among the suggested solutions by considering limitations and materials (step 4). In this step, they used engineering design. The last step includes student groups to present their designs and propose improvements/redesign elements for their designs.

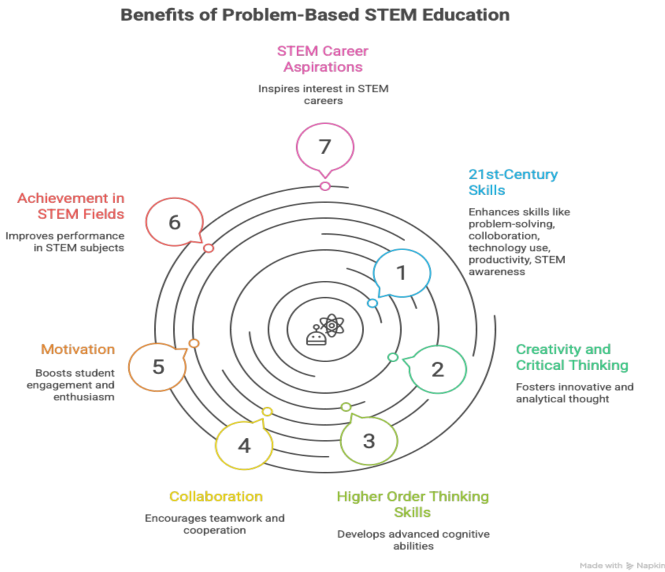

Figure 2. Benefits of Problem-based STEM education

The concept of “design” serves as a means of integrating engineering and technology with other STEM disciplines (Özkızılcık & Cebesoy, 2024). Within this framework, engineering design relies on iterative processes to address problems under specific conditions (Kelly & Sung, 2017). Similar to the teaching sequence proposed by Sari et al. (2018), Abbott (2016) incorporated engineering design into her six-step problem-based STEM teaching sequence (Figure 4). In this sequence, students were first introduced to an authentic problem—disposing of excess dyes directly into water sources. In the second step, they examined the issue from the perspective of scientists and engineers. The third step involved the use of a learning board, which included four guiding questions: (a) What do we know about the problem?, (b) What do we need to find out?, (c) How will we find our answers?, and (d) What is our action plan? The learning board was designed to foster curiosity and sustain students' interest.

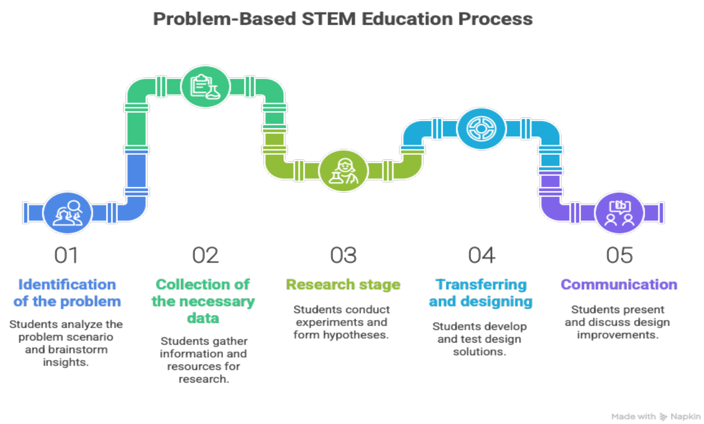

Figure 3. Five-step problem-based STEM teaching sequence (adapted from Sari et al., 2018)

In the fourth step, students conducted research using online resources and reference materials. The fifth step introduced the engineering design process (EDP) cycle (Figure 5), during which students revisited the original problem and attempted to construct a prototype solution—specifically, a filter for removing dyes. Through iterative trials, students refined their designs until they developed a functioning prototype. Finally, in the sixth step, literacy skills were integrated into the process as students documented their learning through journal writing and portfolio preparation.

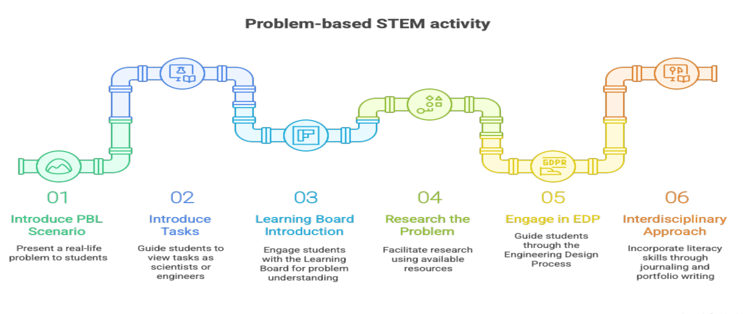

Figure 4. Six-step problem-based STEM teaching sequence (adapted by Abbott, 2016).

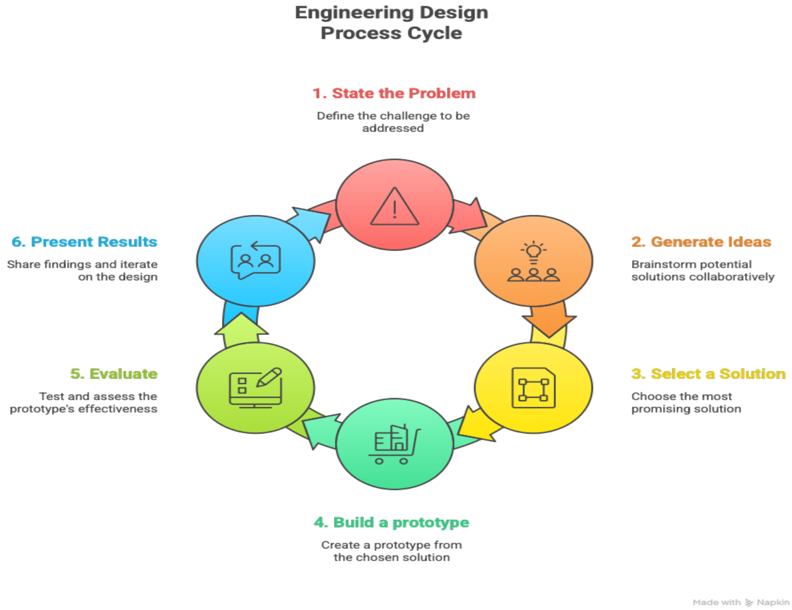

Figure 5. Engineering design cycle

Given that teachers are positioned as facilitators in PBL, this role similarly extends to problem-based STEM instruction. Consequently, scholars have emphasized the need for additional professional development to support teachers in this area (e.g., El Sayary et al., 2015). Nevertheless, studies reveal several persistent challenges, including the absence of well-defined integration models, limited teacher experience, administrative barriers, and insufficient resources (Sahito & Wassan, 2024; Smith et al., 2022). In particular, El Sayary et al. (2015) identified professional development as a critical component for ensuring effective problem-based STEM teaching practices, while Smith et al. (2022) underscored the importance of establishing a shared understanding of problem-based STEM instruction among educators. To address these challenges, 'collective sensemaking through professional dialog' among educators has been proposed (Holmlund et al., 2018, p.17). In this regard, problem-based STEM teaching practices play a crucial role in establishing a shared foundation for the effective implementation of STEM education.

Inquiry-based Learning (IBL)

Like PBL approach, inquiry-based learning is widely recognized as an innovative approach in STEM education shifting the focus from passive knowledge acquisition to active and student-centered learning. Inquiry and therefore inquiry-based learning (IBL) has been a central theme in science education (Strat et al., 2024; Zhong et al. 2022). Within the framework of PBL, students take an active role in learning by employing critical thinking skills—asking questions, planning and conducting investigations, interpreting data as evidence, constructing arguments, developing models, and communicating findings—to deepen their understanding (Anderson, 2002; Crawford, 2014).

Foundation of inquiry-based learning

IBL is rooted in Dewey's (1938) work as which established inquiry in experience (cited in Seland Strat et al., 2024). John Dewey's ideas on inquiry have influenced subsequent work, and various learning cycles such as famous 5E (Engagement, Exploration, Explanation, Elaboration, and Evaluation) adopting inquiry-based learning (IBL) have since been introduced (Oguz Unver & Arabacioglu, 2011). A classic IBL process starts with a question. Students, then, start looking for potential answers and investigate possible solutions. After creating new information chunks, students talk about their findings, experiences and reflect on new piece of information (Savery, 2006). National Research Council (NRC, 2006) identifies five essential characteristics of IBL (see, Figure 6). IBL process begins with engaging students in real-world problem. Students collect relevant data and based on evidences; they formulate hypothesis/explanations. They, then, evaluate explanations and finally, share and define their findings (NRC, 2006).

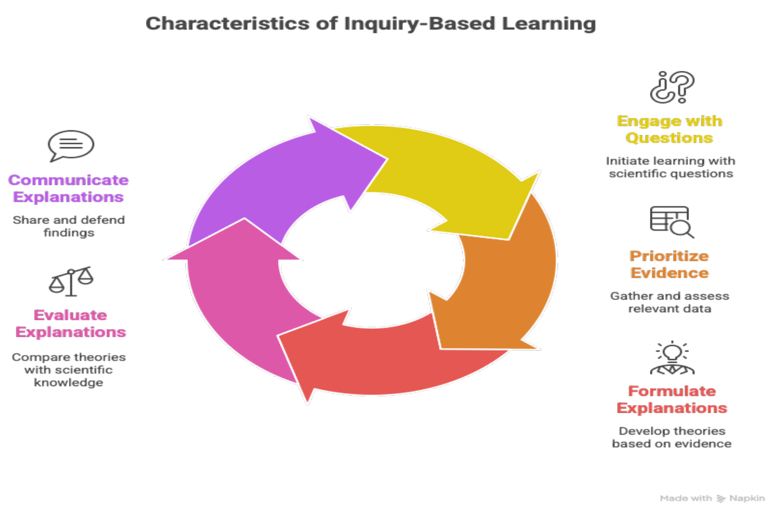

Figure 6. Five essential characteristics of IBL

Types of Inquiry

There is a wide range of inquiry-based learning activities ranging from student-directed open inquiry to teacher-directed organized and guided inquiry (NRC, 2020; Martin- Hansen, 2002):

Structured-inquiry: Students follow a predetermined process to search answers to a question that the teacher has established. Every step is structured and students get comprehensive instructions that culminate in a predetermined discovery.

Guided-inquiry: Students explore teacher-formulated questions and procedures in this type of inquiry. The questions are determined by the teacher who already know possible answers for the problem.

Coupled-inquiry: This kind of inquiry is situated between guided and open inquiry. The teacher lets the students choose an inquiry question from a database of preset queries. However, students are not involved in creating the inquiry question.

Open-inquiry: This kind of inquiry is assumed to be most sophisticated type of inquiry where students create a broad range of inquiry questions while the teacher establishes the knowledge foundation. Students use student-designed or student-selected processes to research topic-related questions during open inquiry. Every step of the open inquiry method involves the students making their own choices (Sadeh & Zion, 2012).

Inquiry-based learning in STEM education

IBL is considered a signature pedagogy of STEM learning (Crippen & Archambault, 2012). The nature, principles, and core concepts of STEM disciplines can be systematically examined and fostered through the application of inquiry-based learning in STEM education (Ješková et al., 2024; Thibaut et al., 2018; Woods-McConney et al., 2020). Inquiry-based learning in STEM is built on active, student-centered approaches in which students work in groups, conduct experiments to build knowledge, and investigate real-world issues (Ješková et al., 2024; Thibaut et al., 2018; Woods-McConney et al., 2020). In this manner, students are expected to pose questions, carry out investigations to make their own discoveries, expected to solve inquiry-based challenges, create knowledge, and collaborate and communicate with others (Zhong et al, 2022)

Affordances inquiry-based STEM education

The literature has documented numerous beneficial outcomes of inquiry-based STEM teaching for students including (a) enhanced cognitive outcomes (Donnelly et al., 2014; Li et al., 2010); (b) greater motivation (Aditomo &

Klieme, 2020; Crawford, 2014; Dilek et al., 2020; Li et al., 2010; Lord & Orkwiszewski, 2006; Sarı et al., 2020); (c) increased flexibility and creativity in addressing problem-solving tasks (Lord & Orkwiszewski, 2006; Sarı et al., 2020; Seland Strat et al., 2024); (d) the enrichment of 21st-century skills (e.g., collaboration, critical thinking, creativity, accountability, persistence, and leadership) (Ješková et al., 2024); (e) improved self-efficacy and self-confidence (Sahito & Wassan, 2024; Strat et al., 2024); (f) the facilitation of integration across disciplines (Rúa Martínez et al., 2024) the development of science process skills (Dilek et al., 2020; Sarı et al., 2020); (g) enhanced awareness of STEM disciplines (Karamustafaoğlu & Pektaş, 2024; Li et al., 2010; Sarı et al., 2020;) and (h) demonstrated higher preferences for future STEM careers (Wang et al., 2021).

Teacher roles

Teachers act as guides and experts who support inquiry through scaffolding, formative assessment, and creating/structuring inquiry-rich learning environments (Nadelson et al., 2013; Roehrig & Luft, 2004). Teacher training is essential for effective inquiry-based STEM. Systematic reviews highlight the need for explicit teacher preparation and ongoing support (Seland Strat et al., 2024; Rúa Martínez et al., 2024).

Approaches for inquiry-based STEM education

Literature illustrates different teaching approaches that could be used for inquiry-based STEM education. These approaches are presented in Figure 7. IBL, PBL, and project-based learning (PjBL) share common characteristics, including their student-centered orientation and emphasis on active learner participation. Accordingly, various instructional models can be employed to support the integration of STEM. One such model is Bybee et al.'s (2006) 5E framework—engage, explore, explain, elaborate, and evaluate—which has been adapted for STEM education (Bybee, 2014). While this model begins with an engaging, essential problem, problem-based STEM activities extend the approach by involving students in solving authentic, real-world problems. When the process additionally entails constructing tangible solutions, such as prototypes or products developed through systematic investigations, it constitutes a specific form of project-based STEM activity. Another possibility involves technology-supported inquiry, which leverages advanced tools such as simulations, animations, and virtual or augmented reality environments.

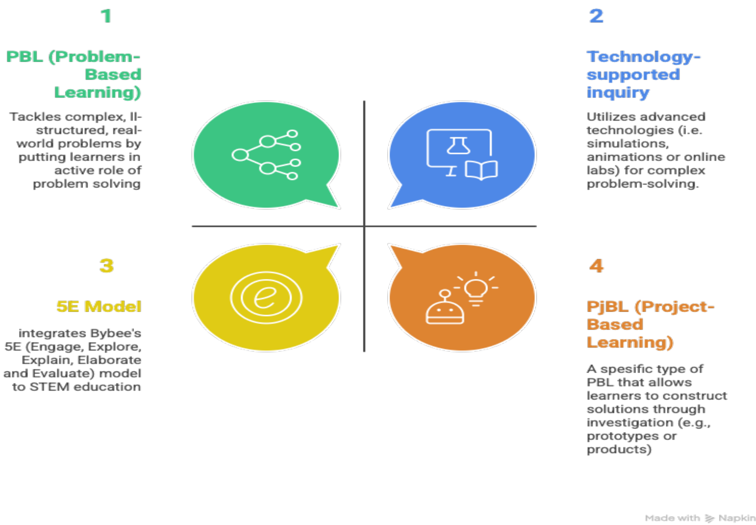

Figure 7. Different approaches for inquiry-based STEM education

To better illustrate how IBL adapted into STEM teaching, Sarı and his colleagues (2020) used a five-step inquiry-based STEM teaching strategy to teach simulation-based physics concepts (see, Figure 8). The adapted Lim (2004)'s five-step inquiry-based learning cycle into an engineering design-based STEM activity using simulations. The first step involved identifying the problem by considering the limitations and constraints. They collected necessary information to solve the problem in planning stage. In third stage, they established hypothesis, designed virtual experiments to test their hypothesis. In construct stage, students chose one of the most suitable solutions, tested, evaluated and developed a prototype. In last stage (reflect), they evaluated their engineering design products and search ways for improvement. In another model, Barry (2014) and Chang and Yang (2014) adopted 5E model into a 6E model for inquiry-based STEM teaching. Their model included (1) engaging, (2) exploring, (3) explaining, (4) engineering (elaborating), (5) enriching, and (6) evaluating steps.

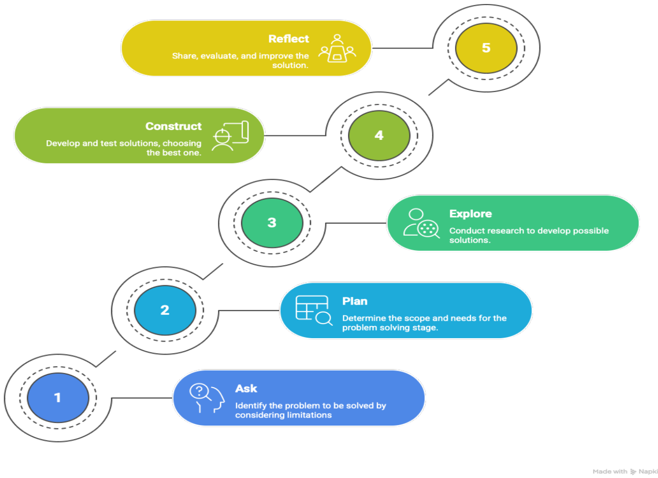

Figure 8. Steps of inquiry-based STEM teaching (adapted from Sarı et al., 2020)

Conclusion

Both problem-based learning (PBL) and inquiry-based learning (IBL) are student-centered approaches that emphasize learners' active engagement in the learning process. In this regard, both approaches can be considered as rooted in constructivist theory which emphasizes the co-construction of meaning through experience and reflection. Since STEM education also prioritizes students' active role in constructing knowledge, PBL and IBL offer a meaningful pedagogical context for teaching STEM. The literature reviewed in this chapter provides valuable insights into how problem-based and inquiry-based STEM teaching methods foster students' learning, motivation, and skills such as critical thinking, creative thinking, and problem solving. Moreover, these approaches have been shown to positively influence students' career aspirations toward STEM fields. This is particularly significant given that numerous national policy documents highlight both the shortage of professionals in STEM disciplines and the declining interest among students in pursuing STEM-related careers.

This chapter also underscores the importance of integrating complementary approaches—such as the 5E instructional model, project-based learning, or the engineering design process (EDP)—into problem-based and inquiry-based STEM education. Such integrations can strengthen the effectiveness of these methods by enhancing learning outcomes. Enriching problem-based and inquiry-based STEM practices with additional frameworks may support the development of more meaningful and structured learning environments for students. In this sense, instructional steps should be clearly articulated and provide sufficient guidance for teachers who intend to implement these integrated models.

The nature of engineering and design processes likewise offers students an authentic context for understanding how engineers work and how products or technologies are created through the engineering design process. Integrating such approaches enables students to experience the practices of engineering and to connect abstract concepts with real-world applications.

Equally important is the role of teachers as facilitators and mentors in problem-based and inquiry-based STEM teaching. Teachers' guidance is essential for navigating the complexities of these pedagogical approaches. However, existing research documents several challenges, including teachers' limited preparation for effectively enacting these roles. Therefore, it is crucial to provide ongoing professional development opportunities to enhance teachers' knowledge, skills, and competencies. Furthermore, teacher education programs should be designed to better prepare future teachers to confidently and effectively implement problem-based and inquiry-based STEM methodologies.

Recommendations

Problem-based and inquiry-based STEM education approaches require careful instructional design and curriculum-level support to realize their full potential. From a constructivist perspective, students must be provided with opportunities to activate and connect their prior knowledge to new conceptual understandings, while also engaging in authentic practices that reflect the epistemic and methodological work of scientists and engineers. Both approaches inherently foster such epistemic agency by situating learners in contexts where knowledge is co-constructed through inquiry, problem solving, and reflection. When STEM curricula systematically embed these pedagogical orientations, students are more likely to experience cognitive, motivational, and aspirational benefits.

However, the effectiveness of these approaches depends heavily on teachers' capacity to scaffold learning, orchestrate inquiry processes, and mediate the complexities of open-ended problem solving. This underscores the need for robust teacher preparation and sustained professional development. Professional learning opportunities should not only provide teachers with practical strategies but also cultivate their pedagogical content knowledge, design thinking, and capacity for reflective practice. Furthermore, the implementation of problem-based and inquiry-based STEM teaching should be conceived as an iterative process, informed by continuous monitoring, feedback, and refinement. Such an approach ensures not only fidelity of implementation but also adaptability to diverse classroom contexts, thereby strengthening the sustainability and scalability of these innovative pedagogies.

Acknowledgements

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References

Abbott, A. (2016). Chemical connections: A problem-based learning, STEM experience. *Science Scope*, *39*(7), 33-42. https://doi.org/10.2505/4/ss16_039_07_33

Aditomo, A., & Klieme, E. (2020). Forms of inquiry-based science instruction and their relations with learning outcomes: Evidence from high and low-performing education systems. *International Journal of Science Education*, *42*(4), 504-525. https://doi.org/10.1080/09500693.2020.1716093

Anazifa, R. D., & Djukri. (2017). Project-based learning and problem-solving skills in science education: Are they effective to improve student's thinking skills?. *Indonesian Journal of Science Education, 18*(2), 146–154. https://doi.org/10.15294/jpii.v6i2.11100

Anderson, R. D. (2002). Reforming science teaching: What research says about inquiry. *Journal of Science Teacher Education*, *13*(1), 1-12. https://doi.org/10.1023/A:1015171124982

Barry, N. B. (2014). The ITEEA 6E learning by DeSIGN model. *Technology and Engineering Teacher*, *73*(6), 14–19.

Beier, M. E., Kim, M. H., Saterbak, A., Leautaud, V., Bishnoi, S., & Gilberto, J. M. (2018). The effect of authentic project-based learning on attitudes and career aspirations in STEM. *Journal of Research in Science Teaching, 56*(1), 3–23. https://doi.org/10.1002/tea.21465

Boix Mansilla, V. (2010). Learning to synthesize: The development of interdisciplinary understanding. In R. Frodeman, J. T. Klein, C. Mitcham, & J. B. Holbtook (Eds), *Oxford Handbook of Interdisciplinarity* (pp. 288–306). Oxford University Press.

Bybee, R. W. (2014). Guest editorial: The BSCS 5E instructional model: Personal reflections and contemporary implications. *Science and Children*, *51*(8), 10-13. https://doi.org/10.2505/4/sc14_051_08_10

Bybee, R., Taylor, J., Gardner, A., Van Scotter, P., Powell, J., Westbrook, A., et al. (2006). *The BSCS 5E instructional model: Origins, effectiveness and applications* (Vol. 5, pp. 88–98). Biological Sciences Curriculum Study.

Cebesoy, Ü. B. (2023). Probleme dayalı STEM uygulamaları [Problem-based STEM applications]. In E. Kaya & B. Yıldırım (Eds.). *STEM eğitimine yolculuk: STEM eğitiminde öğrenme yolları* (pp.213-231). Nobel Akademik Yayıncılık.

Chang, Y. S., & Yang, Y. (2014). An exemplar of STEM teaching design-

Hydraulic arm. *Technology and Human Education Quarterly*, *1*(1), 2–17.

Coufal, P. (2022). Project-Based STEM Learning Using Educational Robotics as the Development of Student Problem-Solving Competence. *Mathematics, 10*(23). 4618. https://doi.org/10.3390/math10234618

Crawford, B. A. (2014). From inquiry to scientific practices in the science classroom. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of Research on Science Education, Volume II* (pp. 515–541). Routledge.

de Graaff, E., & Kolmos, A. (2003). Characteristics of problem-based learning. *International Journal of Engineering Education*, *19*(5), 657-662.

Dilek, H., Taşdemir, A., Konca, A. S., & Baltacı, S. (2020). Preschool children's science motivation and process skills during inquiry-based STEM activities. *Journal of Education in Science Environment and Health*, *6*(2), 92-104. https://doi.org/10.21891/jeseh.673901

El Sayary, A. M. A., Forawi, S. A., ve Mansour, N. (2015). STEM education and problem-based learning. In Wegerif, R., Li, L., & C., K. J. (Eds.). *The Routledge International Handbook of Research on Teaching Thinking*, (ss. 357-369). Routledge.

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn?. *Educational Psychology Review*, *16*, 235-266. https://doi.org/10.1023/B:EDPR.0000034022.16470.f3

Holmlund, T. D., Lesseig, K., & Slavit, D. (2018). Making sense of "STEM education" in K-12 contexts. *International Journal of STEM Education*, *5*, 32. https://doi.org/10.1186/s40594-018-0127-2

Hung, W., Jonassen, D. H., ve Liu, R. (2008). Problem-based learning. In J.M. Spector, J. G. Van Merriënboer, M.D., Merrill, & M. Driscoll (Ed). *Handbook of Research on Educational Communications and Technology* (pp. 485-506). Routledge.

Ješková, Z., Lukáč, S., Šnajder, Ľ., Guniš, J., Klein, D., & Kireš, M. (2022). Active learning in STEM education with regard to the development of inquiry dkills. *Education Sciences*. https://doi.org/10.3390/educsci12100686

Karamustafaoğlu, O., & Pektaş, H. M. (2023). Developing students' creative problem solving skills with inquiry-based STEM activity in an out-of-school learning environment. *Education and Information Technologies*, *28*(6), 7651-7669. https://doi.org/10.1007/s10639-022-11496-5

Kelley, T. R., & Sung, E. (2017). Examining elementary school students' transfer of learning through engineering design using think-aloud protocol analysis. *Journal of Technology Education, 28*(2), 83–108. https://doi.

org/10.21061/jte.v28i2.a.5

Kilroy, D. A. (2004). Problem based learning. *Emergency Medicine Journal*, *21*(4), 411-413. http://dx.doi.org/10.1136/emj.2003.012435

Li, Q., Moorman, L., & Dyjur, P. (2010). Inquiry-based learning and e-mentoring via videoconference: a study of mathematics and science learning of Canadian rural students. *Educational Technology Research and Development*, *58*(6), 729-753. https://doi.org/10.1007/s11423-010-9156-3

Lord, T., & Orkwiszewski, T. (2006). Moving from didactic to inquiry-based instruction in a science laboratory. *The American Biology Teacher*, *68*(6), 342-345. https://doi.org/10.1662/0002-7685(2006)68[342:DTIIIA]2.0.CO;2

Mabley, S., Ventura-Medina, E., & Anderson, A. (2020). 'I'm lost'–a qualitative analysis of student teams' strategies during their first experience in problem-based learning. *European Journal of Engineering Education*, *45*(3), 329-348. https://doi.org/10.1080/03043797.2019.1646709

Martin-Hansen, L. (2002). Defining inquiry. *The Science Teacher, 69*, 34–37.

Nadelson, L. S., Callahan, J., Pyke, P., Hay, A., Dance, M., & Pfiester, J. (2013). Teacher STEM perception and preparation: Inquiry-based STEM professional development for elementary teachers. *The Journal of Educational Research*, *106*(2), 157-168. https://doi.org/10.1080/00220671.2012.667014

National Research Council (NRC). (2000). Inquiry and the national science education standards. National Academy.

Oguz Unver, A., & Arabacioglu, S. (2011). Overviews on inquiry based and problem based learning methods. *Western Anatolia Journal of Educational Sciences (WAJES), Special Issue: Selected papers presented at World Conference on New Trends in Science Education (WCNTSE),* 303-310.

Ozkizilcik, M., & Cebesoy, U.B. (2024). The influence of an engineering design-based STEM course on pre-service science teachers' understanding of STEM disciplines and engineering design process. *International Journal of Technology and Design Education,* 34, 727–758. https://doi.org/10.1007/s10798-023-09837-7

Rehmat, A. P., & Hartley, K. (2020). Building engineering awareness: Problem based learning approach for STEM integration. *Interdisciplinary Journal of Problem-Based Learning*, *14*(1). https://doi.org/10.14434/ijpbl.v14i1.28636

Roehrig, G. H., & Luft, J. A. (2004). Constraints experienced by beginning secondary science teachers in implementing scientific inquiry lessons. *International Journal of Science Education*, *26*(1), 3-24. https://doi.org/10.1080/0950069022000070261

Rúa Martínez, F. D. J., Merchán Merchán, M. A., & Camacho-Tamayo, E. (2024). Teaching sequences based on the STEM approach for the development of inquiry in early childhood education: A systematic review. *Eurasia Journal of Mathematics, Science and Technology Education, 20*(10), em2517. https://doi.org/10.29333/ejmste/15207

Sadeh, I., & Zion, M. (2012). Which type of inquiry project do high school biology students prefer: Open or guided?. *Research in Science Education*, *42*(5), 831-848. https://doi.org/10.1007/s11165-011-9222-9

Sahito, Z., & Wassan, S. H. (2024). Literature review on STEM education and its awareness among teachers: An exploration of issues and problems with their solutions. *Sage Open*, *14*(1), 21582440241236242. https://doi.org/10.1177/215824402412362

Savery, J. R. (2015). Overview of problem-based learning: Definitions and distinctions. In A. Walker, H. Leary, C.E. Hmelo-Silver, & P. A. Ertmer (Eds). Essential Readings in Problem-Based Learning: Exploring and Extending the Legacy of Howard s. Barrows, Purdue University Press.

Servant-Miklos, V. F. (2019). Fifty years on: A retrospective on the world's first problem-based learning programme at McMaster University Medical School. *Health Professions Education*, *5*(1), 3-12. https://doi.org/10.1016/j.hpe.2018.04.002

Slough, S. W., & Milam, J. O. (2013). Theoretical framework for the design of STEM Project-Based Learning. In R. M. Capraro, M. M. Capraro, & J. Morgan (Eds.), STEM project-based learning: An integrated science, technology, engineering, and mathematics (STEM) approach (pp. 15-27). Rotterdam, The Netherlands: Sense Publishers.

Smith, K., Maynard, N., Berry, A., Stephenson, T., Spiteri, T., Corrigan, D., ... & Smith, T. (2022). Principles of problem-based learning (PBL) in STEM education: Using expert wisdom and research to frame educational practice. *Education Sciences*, *12*(10), 728. https://doi.org/10.3390/educsci12100728

Strat, T. T. S., Henriksen, E. K., & Jegstad, K. M. (2024). Inquiry-based science education in science teacher education: a systematic review. Studies in Science Education, 60(2), 191-249. https://doi.org/10.1080/03057267.2023.2207148

Taylor, D., & Miflin, B. (2008). Problem-based learning: Where are we now?. *Medical Teacher*, *30*(8), 742-763. https://doi.org/10.1080/01421590802217199

Thibaut, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., ... & Depaepe, F. (2018). Integrated STEM education: A systematic review of instructional practices in secondary education. *European Journal of STEM Education*, *3*(1), 2. https://doi.org/10.20897/ejsteme/85525

Wang, H. H., Lin, H. S., Chen, Y. C., Pan, Y. T., & Hong, Z. R. (2021). Modelling relationships among students' inquiry-related learning activities, enjoyment of learning, and their intended choice of a future STEM career. *International Journal of Science Education*, *43*(1), 157-178. https://doi.org/10.1080/09500693.2020.1860266

Warnock, J. N., & Mohammadi-Aragh, M. J. (2016). Case study: use of problem-based learning to develop students' technical and professional skills. *European Journal of Engineering Education*, *41*(2), 142-153. https://doi.org/10.1080/03043797.2015.1040739

Wood, E. J. (2004). Problem-based learning: Exploiting knowledge of how people learn to promote effective learning. *Bioscience Education, 3*(1), 1–12. https://doi.org/10.3108/beej.2004.03000006

Woods-McConney, A., McConney, A., & Sturrock, K. (2020). Inquiry-based teaching and learning in Primary STEM. In A. Fitzgerald, C. Haeusler, & L Pfeiffer (Eds.). *STEM Education in Primary Classrooms* (pp. 28-44). Routledge.

Yew, E. H., & Goh, K. (2016). Problem-based learning: An overview of its process and impact on learning. *Health Professions Education*, *2*(2), 75-79. https://doi.org/10.1016/j.hpe.2016.01.004

Zhong, B., Liu, X., Xia, L., & Sun, W. (2022). A proposed taxonomy of teaching models in STEM education: Robotics as an example. *Sage Open*, *12*(2), 21582440221099525. https://doi.org/10.1177/21582440221099525

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Chapter 3

Gamification Strategies in STEM Education

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Chapter Highlights

This chapter examines gamification as an instructional approach in STEM education, focusing on its potential to enhance student engagement, motivation, and learning outcomes. By drawing on theoretical frameworks and empirical findings, it explores how gamified learning environments can address diverse learner needs while also considering implementation challenges and future research directions.

- Role of Gamification in STEM – Examines how gamification enhances student engagement and learning outcomes across STEM disciplines.
- Theoretical Foundations – Discusses key frameworks such as intrinsic motivation theory and flow theory to explain the effectiveness of gamified learning.
- Instructional Strategies – Explores a range of gamification techniques applied in different STEM contexts and subject areas.
- Student Outcomes and Diversity – Analyzes the impact of gamified learning on students from diverse backgrounds, including motivation, achievement, and satisfaction.
- Challenges and Limitations – Identifies critical issues such as demographic differences, implementation difficulties, and limited long-term empirical evidence.

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Introduction

STEM education, which combines science, technology, engineering, and mathematics, is very important in helping students to develop skills of critical thinking, creativity, and solving problems. This kind of interdisciplinary approach prepares learners to face the fast changes of modern technology and society (Jindal et al., 2023). In current practice, STEM teaching often uses methods such as problem-based, inquiry-based, project-based, and cooperative learning. These strategies give students chance to work together on interdisciplinary tasks, so they can strengthen their ability in problem solving and critical thinking (Ravi et al., 2023). Recently, teachers also try to use more personalized methods, so that learning can be adjusted to the needs of each student and give better results (Bontchev et al., 2024). Gamification in the classroom means using game elements in situations outside of real games, with the purpose to increase motivation and engagement of students (Palomino et al., 2023; Vrcelj et al., 2023). It usually includes points, badges, leaderboards, and other rewards to make lessons more interactive and enjoyable (Al-Hafdi & Alhalafawy, 2024). This technique is useful especially for subjects that sometimes look difficult or boring, because it offers another way to attract student attention (De Sousa Borges et al., 2014). By making lessons more enjoyable, gamification can support students to achieve learning goals in more effective way (Feng et al., 2024).

One of the common problems in STEM education is low motivation and lack of interest from students. Gamification can help to solve this issue by creating learning activities that are more engaging and exciting (Dicheva et al., 2023). Studies also show that when digital rewards such as badges or points are used, students show better performance and interest in learning, for example in physics lessons (Andrade et al., 2020). At the same time, gamification helps students to adapt to new learning situations and reduce negative feeling about competition (Funa et al., 2021). However, it is necessary that gamification is designed carefully, so it can fit both individual and group learning processes (Borges et al., 2016). By using gamification in STEM education gives strong potential to improve student motivation and engagement. If teachers combine it with innovative teaching methods and personalized learning, the classroom can become more effective and also more enjoyable for students (Klock et al., 2018; Sawarkar et al., 2024).

Theoretical Foundations of Gamification in STEM Education

Gamification in STEM education is the use of game design elements to make students more engaged, motivated, and able to remember what they learn.

The main theories that explain gamification are Constructivism, Behaviorism, Self-Determination Theory (SDT), and Flow Theory. Constructivism says students learn better when they create knowledge from their own experience, and this matches with gamification because it is interactive in nature (Rukadikar & Khandelwal, 2025; Daungtod & Chaijareon, 2019). Behaviorism talks about reinforcement and conditioning, and in gamification this can be seen in the use of points or badges that reward positive actions (Landers et al., 2015). SDT focuses on the human need for competence, autonomy, and relation with others. In gamification, this theory is important because it gives internal motivation when students get choices and social connection (Schaper et al., 2022; Sangroya & Kabra, 2023). Flow Theory explains the condition where students are fully concentrated and enjoy the task, and gamification can create this situation when the task is difficult but still possible, and feedback is given quickly (Rukadikar & Khandelwal, 2025; Sangroya & Kabra, 2023).In STEM education, different game strategies are used such as points, leaderboards, badges, and storytelling. Points and leaderboards bring competition and feeling of success, which make students more motivated and active in learning (Chatzidaki et al., 2025; Jun & Lucas, 2025). Badges alone are not so strong, but when combined with other elements they make the gamified system more powerful (Chatzidaki et al., 2025). Storytelling elements, like the hero's journey, can create immersive and meaningful lessons, which help students connect to the topic and remember it longer (Sotirov et al., 2024). Studies also show these strategies improve academic results and keep motivation longer in gamified learning environments (Jun & Lucas, 2025; Jaskari & Syrjälä, 2024)

Even so, gamification in STEM education must be designed with care. It needs to match the goals of the lesson and take into account the different needs of students. A good gamification design should not only give external rewards, but also increase internal motivation, so students do not depend only on surface incentives (Jaskari & Syrjälä, 2024; Leong, 2025). The design should give clear challenges, fast feedback, and support the psychological needs of learners, so they stay engaged and go deeper in their learning (Sangroya & Kabra, 2023). It is also important to review and improve gamified strategies from time to time, so they continue to fit the changes in student needs and bring maximum benefit in education (Chatzidaki et al., 2025; Leong, 2025).In conclusion, gamification in STEM education is supported by strong learning theories, and it uses points, leaderboards, badges, and narratives to make learning more engaging and effective. But its success depends on careful design and continuous adjustment, so that it can achieve the learning goals and also answer the diverse needs of students.

Table 1. Summary table of Theoretical Foundations of Gamification

Aspect	Findings	Sources
Theoretical Foundations	Constructivism: Active learning through experiences	(Rukadikar & Khandelwal, 2025), (Daungtod & Chaijareon, 2019)
	Behaviourism: Reinforcement through rewards (points, badges	(Landers et al., 2015), (Banerjee et al., 2024)
	Self-Determination Theory (SDT): Competence, autonomy, relatedness	(Schaper et al., 2022),(Sangroya & Kabra, 2023)
	Flow Theory: Deep immersion through challenging tasks and feedback	(Sangroya & Kabra, 2023) (Rukadikar & Khandelwal, 2025),
Game Strategies	Points and Leaderboards: Competition and achievement	(Chatzidaki et al., 2025), (Jun & Lucas, 2025)
	Badges: Supplementary motivation	(Banerjee et al., 2024), (Chatzidaki et al., 2025)
	Narrative Elements: Immersive learning paths	(Velazquez-Garcia et al., 2025)
Design	Alignment with Objectives: Tailored to instructional goals	(Jaskari & Syrjälä, 2024), (Leong, 2025)

Key Gamification Strategies for STEM Learning

Game-based Learning and Gamification as Two Concepts

Game-based learning (GBL) and gamification are two different but related methods in education. GBL uses real games as a tool to support learning, taking advantage of the fun and interactive nature of games to teach certain knowledge or skills. On the other hand, gamification does not use full games but brings game elements like points, badges, or leaderboards into normal learning to make students more motivated and engaged (Studart, 2022; Chung et al., 2025; Dahalan et al., 2024). The main difference is that GBL focuses on games themselves as the learning medium, while gamification applies game mechanics inside traditional lessons to create more attractive experience.Research shows that both methods give positive impact on student motivation, participation, and learning outcomes (Chung et al., 2025; Zabala-Vargas et al., 2021; Vasbieva & Kalugina, 2024). For example, GBL has been used in engineering education to help students understand and remember difficult concepts more effectively (Zabala-Vargas et al., 2021). At the same time, gamification has been proven useful for improving motivation and interest in many contexts, such as language classes and vocational training (Dahalan et al., 2024; Vasbieva & Kalugina, 2024).

Use of Points, Badges, and Leaderboards (PBL) as Motivational Tools for Students

Points, badges, and leaderboards (PBL) are the most common elements used in gamification for education. These features act as external motivators, giving students quick feedback and recognition for what they achieve (Daud et al., 2017; Denden et al., 2020; Badea & Popescu, 2024). Points are usually given when students finish tasks or reach certain goals. Badges work as visual symbols to show accomplishments, while leaderboards arrange students according to performance, creating competition (Daud et al., 2017; Denden et al., 2020). Many studies report that PBL can increase student motivation and participation because it makes the classroom more competitive and rewarding (Daud et al., 2017; Denden et al., 2020; Badea & Popescu, 2024).Still, the impact of these elements is not the same for every student or learning context. Some learners enjoy competition and do better with leaderboards, but others may lose interest if they always stay at the bottom rank (Daud et al., 2017). Because of this, teachers need to design and balance PBL carefully so it can suit the different needs and preferences of students (Daud et al., 2017; Denden et al., 2020).

Role-playing and Simulation, with Advanced Techniques of Immersive Gamification

Role-playing and simulation are higher-level gamification methods that give students immersive and interactive learning experience. With these approaches, learners can take part in realistic situations, practice important skills, and get feedback directly, which helps them to learn better and remember longer (Otemaier et al., 2024; Teerawongpairoj et al., 2024; Li & Edwards, 2020). In STEM education, role-playing games (RPGs) and simulations are very useful because applying theory into practice is a key part of the learning process (Otemaier et al., 2024; Teerawongpairoj et al., 2024).For example, role-playing has been used with software engineering students to train them in requirement elicitation interviews, and this activity improved both engagement and performance (Otemaier et al., 2024). In the same way, gamified simulations in virtual reality (VR) give safe and controlled environments for students to practice complex skills, and this improves motivation and learning results (Kwok et al., 2023).These advanced gamification techniques not only make the lesson more interesting, but also help students to build skills in critical thinking, problem solving, and teamwork (Otemaier et al., 2024; Teerawongpairoj et al., 2024; Kwok et al., 2023).

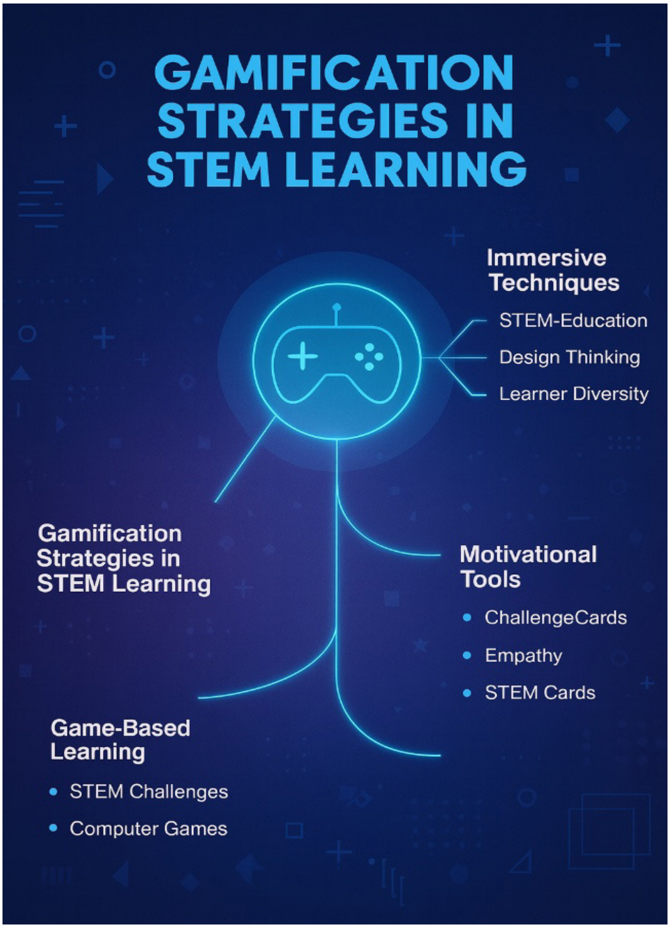

Figure 1. Gamification Strategies in STEM Learning

In conclusion, both game-based learning (GBL) and gamification are useful methods to improve STEM education. GBL uses the learning power of games directly, while gamification brings game mechanics into normal classroom to increase student interest and motivation. Using points, badges, and leaderboards can encourage learners, but the design must think about different student needs. More advanced methods such as role-playing and simulation give immersive learning that improve practical skills and engagement, which is very important in STEM field. With more studies in the future, these approaches show strong potential to build learning that is more attractive and more effective.

Technological Tools and Platforms for Gamified STEM Education

STEM-focused educational games and interactive simulation exercises (Minecraft: Education Edition, Kahoot!).

The use of technology tools and platforms in gamified STEM education shows strong potential to improve student engagement, motivation, and learning results. Two popular examples are Minecraft: Education Edition and Kahoot!, which are often used as STEM games and interactive activities. Minecraft: Education Edition, built from the famous game Minecraft, is applied in classrooms to create immersive and metaverse-like learning spaces. Studies show it helps students to feel social presence, empathy, and active participation, especially in subjects such as Chemistry, Coding, and AI (Singh & Sun, 2025). Its success also comes from creating immersion with challenge, flow, and competence (Singh & Sun, 2025). Another strength of Minecraft is supporting collaboration, because students can work together on tasks, which leads to better academic results and stronger inner motivation (Zheng & Wang, 2023).

Kahoot! is different, as it is mainly a gamified quiz platform where teachers prepare and run quizzes in a playful style. Research shows Kahoot! has positive impact on engagement, motivation, and understanding of lessons (Balaskas et al., 2023; López et al., 2022). For example, in a study with Grade 6 students, adding Kahoot! to normal teaching increased interest, enjoyment, and sense of autonomy (Balaskas et al., 2023). In higher education, students who used Kahoot! quizzes also achieved better results than those who did not, but researchers note the tool alone cannot guarantee success (López et al., 2022). The platform works well because it creates a creative and supportive learning environment, which encourages students to participate actively (Balaskas et al., 2023). Overall, both Minecraft: Education Edition and Kahoot! show the power of gamified tools in changing STEM education into more interactive, engaging, and effective learning. In conclusion, using these tools in STEM classrooms has been proven to improve student motivation, engagement, and outcomes. They apply gamification principles to design immersive experiences that make difficult STEM concepts easier and more enjoyable. As technology keeps developing, such tools will become even more important for the future of STEM education.

Table 2. Educational Tools in STEM Gamification: Features, Impacts, and Empirical Findings

Tool	Key Features	Educational Impact	Study Findings
Minecraft: Education Edition	Metaverse-like environment Collaborative tasks - Immersive learning	Enhances social presence Fosters empathetic engagement Promotes behavioral involvement	Significant contribution to immersion through competence, flow, and challenge (Singh & Sun, 2025) Improved academic performance and intrinsic motivation through collaborative learning (Zheng & Wang, 2023) Positive impact on interest, enjoyment, and autonomy (Balaskas et al., 2023)
Kahoot!	Gamifiedquizzes Mobile-friendly Real-time feedback	Increases student engagement Enhances motivation and understanding Encourages autonomous learning	Better academic performance in higher education (López et al., 2022)

Application of virtual and augmented reality (VR/AR) in teaching STEM disciplines.

The use of Virtual Reality (VR) and Augmented Reality (AR) in STEM teaching has become more popular in recent years because of their ability to give immersive and interactive learning experience. These technologies can increase student engagement, motivation, and understanding of difficult concepts by offering dynamic and real-time interaction with virtual objects (Guerra et al., 2024; Giang et al., 2025; Al-Azawi et al., 2019; Kononov et al., 2025). For example, AR and VR can change abstract STEM ideas into more concrete experience, so subjects like chemistry, physics, and engineering become easier to understand and more meaningful (Momenipour et al., 2024; Adetunla et al., 2024). In higher education, these tools are useful to build cross-disciplinary skills such as creating mathematical models and learning spatial relations (Alexandrovna et al., 2024; Huang & Tseng, 2025). AR and VR also help in making virtual learning environments (VLEs) for distance education, which can remove geographical barriers and give access to quality education for students living far from campus (Guerra et al., 2024; Al-Azawi et al., 2019). However, there are also challenges in using VR and AR for STEM learning. The high price of devices, the need for strong infrastructure, and the difficulty for teachers to learn the system are big barriers to adoption (Al-Azawi et al., 2019; Momenipour et al., 2024; Prieto Andreu, 2025). There are also health concerns like eye strain or motion sickness when using for long time, and sometimes the content may not match cultural context (Al-Azawi et al., 2019). For better integration, schools and universities must plan carefully and align education, organization, and technology strategies together (Momenipour et al., 2024). Future research should try to develop suitable pedagogy, provide metacognitive support, and test blended models like flipped classroom to increase the benefit of AR and VR (Ibáñez & Delgado-Kloos, 2018; Tene et al., 2024). More long-term studies are also needed to see the real effect on learning results and to solve current problems with technical limitations and usability (Prieto Andreu, 2025; Tene et al., 2024). In conclusion, VR and AR have strong potential to transform STEM education by making learning more interactive and engaging. But their success depends on solving challenges of cost, infrastructure, and teaching methods. With careful research and planning, these technologies can play important role in the future of STEM education.

Mobile and internet apps and websites with gamified interfaces for children interested in STEM.

The use of gamified interfaces in mobile and online applications for children who are learning STEM (Science, Technology, Engineering, and Mathematics) has shown good results for improving engagement, motivation, and learning success. Many studies examine how gamification works in education, especially in informal learning and in specific STEM subjects. For example, one study with a gamified web app for Grade 5 students found that points and leaderboards increased motivation by giving feeling of success and competition, while badges were less effective (Chatzidaki et al., 2025). Another mobile app created to teach fractions for Grade 4 students reported high satisfaction for usability and also positive impact on learning (Solano-Gonzales et al., 2023). A different study showed that combining spaced repetition with gamification in a mobile learning system for K-12 could be very useful for STEM education (Yeh et al., 2016).

Table 3. Gamified Applications in STEM Education: Study Focus, Key Findings, and Implications

Study Focus	Key Findings	Implications
Gamified web application for fifth-grade students (Chatzidaki et al., 2025)	Points and leaderboards increased motivation; badges less effective	Gamification elements can enhance motivation and engagement in informal learning settings
Mobile application for teaching fractions (Solano-Gonzales et al., 2023)	High satisfaction in usability; positive impact on learning outcomes	Gamified mobile apps can improve learning in specific STEM subjects
Spaced repetition and gamification in mobile learning(Yeh et al., 2016)	Potential for fruitful results in STEM education	Combining instructional strategies with gamification can enhance learning outcomes
Gamified mobile app for physical activity (Schafer et al., 2018)	Effective in encouraging physical activity	Gamified feedback can motivate children to engage in healthy behaviors
SmartGame project (Gini et al., 2023)	Supports math learning and fosters interpersonal relationships	Integration of gamified apps with tangible devices can enhance educational experiences
Gamification with modern technologies (Logothetis et al., 2022)	Increased engagement, motivation, and development of soft skills	Combining gamification with advanced technologies can enhance learning experiences
Gamified music note instruction app (Chumpanin et al., 2024)	Enjoyable and intuitive learning experience	Gamification can be effectively applied to non-STEM subjects for educational purposes

Gamified interfaces are also used outside of classroom lessons. One mobile app used to promote physical activity in children applied smartphone sensors to give motivational feedback, and this was effective for encouraging them to be active (Schafer et al., 2018). The SmartGame project joined a gamified web app with an IoT device to help children learn mathematics and improve social relations, especially for those who lost interaction during the pandemic (Gini et al., 2023). A study in Turkey that looked at STEM apps for children found that most apps focused on science and math, but many were missing features such as social interaction or progress tracking (Konca et al., 2024). This shows designers need to make more complete and interactive educational tools.The literature also notes the importance of continuous checking and improvement of gamified tools to fit different types of learners and reduce possible negative impact. One study on gamification in informal science learning stressed that regular evaluation is needed to make these approaches more effective (Chatzidaki et al., 2025). Also, when gamification is combined with new technologies such as virtual worlds and geolocation, it can further increase engagement and motivation, while also building soft skills and positive learning attitude (Logothetis et al., 2022). Gamified interfaces are not limited to STEM only. For example, in music education, a mobile web application with gamification design helped beginners learn music notes in an enjoyable and simple way (Chumpanin et al., 2024). In short, gamified interfaces in mobile and internet applications for children show strong potential to improve engagement, motivation, and learning in STEM. But these tools must be evaluated and improved continuously to make sure they meet the needs of different learners and provide more complete educational experience. The mix of gamification with modern technologies and creative teaching strategies looks very promising for the future of STEM education.

Future Directions and Innovations in Gamification for STEM

The role of AI and adaptive learning in the future of gamification

The use of artificial intelligence (AI) and adaptive learning in gamification for STEM education is expected to change the education system by making learning more personal, engaging, and effective. AI makes gamification stronger by giving real-time feedback, adaptive learning paths, and personalized content for each student. This is possible because AI can study student data and then change the material according to the learner's level, so every student gets the right challenge and support (Kok et al., 2024; Ashley, 2025; Velazquez-Garcia et al., 2025; Mitchell, 2025). For example, the MagicSchool AI platform helps teachers by automating administrative work and creating lesson plans that are customized. In this way, teachers can spend more time on project-based and interactive activities (Ashley, 2025). AI-based gamification can also promote critical thinking, teamwork, and creativity by linking classroom knowledge with real-world problems, so the learning becomes more interesting and meaningful (Ashley, 2025; Bugri & Egala, 2025).The future of gamification with AI and adaptive learning also brings some challenges and ethical issues. Problems like data privacy, bias in algorithms, and the digital divide need careful attention to make sure all students can use these tools fairly (Velazquez-Garcia et al., 2025; Aravind et al., 2025; Bushuyev et al., 2025). Even with these challenges, the benefits are large. AI can manage assessment and provide smart tutoring systems that give feedback and adjust the speed of learning. This is important for keeping students motivated and active (Velazquez-Garcia et al., 2025; Kassenkhan et al., 2025; Srimathi & Anitha, 2025). Also, AI with gamification can help students build important skills like computational thinking, problem solving, and independent decision-making, which are very important in STEM education (Kassenkhan et al., 2025; Tian, 2024). As more schools and universities start to use these technologies, continuous research and changes will be needed to make sure the systems are applied well and give the best results for students (Bushuyev et al., 2025; Bennani et al., 2022).AI and adaptive learning in gamification for STEM education have strong potential to create learning environments that are more personalized, engaging, and effective. By solving the challenges and ethical issues, educators can use these technologies to improve learning outcomes and prepare students better for future success in STEM.

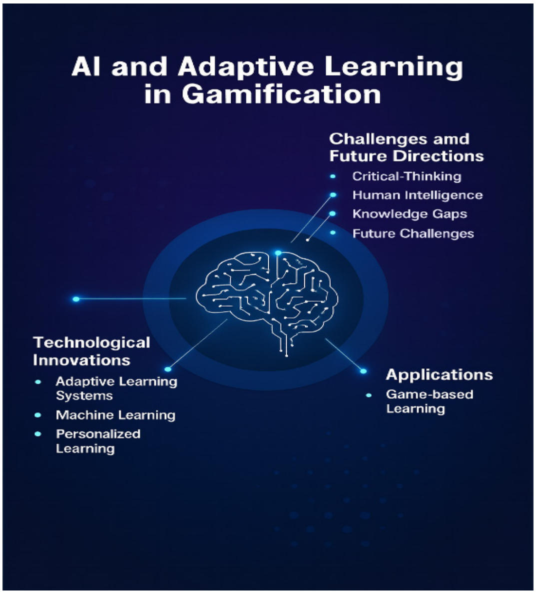

Figure 2. AI and Adaptive Learning in Gamification

Trends That Could Disrupt Labs: Gamification, Blockchain Credentials & Metaverse Learning

The mix of gamification, blockchain credentials, and metaverse learning is becoming an important change in education, with strong potential to transform traditional laboratory practices and improve student learning experience. Gamification, which means using game mechanics in non-game situations, is now seen as a useful method to raise student engagement and motivation. By adding features like points, badges, and leaderboards, gamification can turn normal learning tasks into fun and interactive activities. Many studies show that this approach can improve learning results and make students participate more actively (Tjahjono et al., 2022; Lukita et al., 2024). Blockchain, on the other side, provides secure and transparent way to verify academic records. With decentralized ledgers, blockchain makes credentials tamper-proof and easy to check, increasing trust in educational documents (Tjahjono et al., 2022; Al-Kfairy et al., 2025; Razzaq et al., 2024). The combination of gamification and blockchain can build new education systems that are both motivating and secure, offering a strong framework for modern learning (Tjahjono et al., 2022; Lukita et al., 2024).

The metaverse, which is a virtual world that connects physical and digital spaces, is also seen as a big change for future learning. It uses technologies like virtual reality (VR), augmented reality (AR), and artificial intelligence (AI) to make virtual classrooms, simulations, and gamified learning settings (Al-Kfairy et al., 2025; Peng et al., 2024; Son et al., 2024). These immersive environments can raise student motivation, engagement, and make education more inclusive and easier to access (Al-Kfairy et al., 2025; Peng et al., 2024). Real examples include virtual labs such as SimLab, which give hands-on practice and often produce better results than traditional labs (Son et al., 2024). The metaverse can also support teamwork and reduce the gap between theoretical study and industry practice (Son et al., 2024). But, challenges remain such as high cost of infrastructure, rules and regulations, and ethical concerns, especially about AI decisions (Al-Kfairy et al., 2025; Bushuyev et al., 2025). Future research needs to address these barriers and test the scalability of these approaches to ensure they work effectively (Al-Kfairy et al., 2025; Bushuyev et al., 2025; Hajian et al., 2024). By bringing together gamification, blockchain, and the metaverse has great potential to change education by making it more engaging, secure, and inclusive. However, success will depend on solving problems of infrastructure, regulation, and ethics. More studies are required to overcome these issues and to fully use the transformative power of these new educational technologies.

Table 4. Emerging Trends in Education: Benefits and Challenges of Gamification, Blockchain Credentials, and Metaverse Learning

Trend	Description	Benefits	Challenges	Challenges
Gamification	Application of game mechanics to education	Increased engagement and motivation, improved learning outcomes	Implementation complexity, need for effective design	(Tjahjono et al., 2022) (Lukita et al., 2024)
Blockchain Credentials	Decentralized and secure method for credential verification	Tamper-proof records, enhanced integrity of credentials	Tamper-proof records, enhanced integrity of credentials	(Tjahjono et al., 2022) (Al-Kfairy et al., 2025) (Razzaq et al., 2024)
Metaverse Learning	Virtual environments combining physical and digital realities	Immersive experiences, enhanced engagement, inclusive learning	High infrastructure costs, ethical considerations in AI	(Al-Kfairy et al., 2025) (Peng et al., 2024) (Son et al., 2024)

Policy recommendations for institutional adoption and sustainability

When talking about policy recommendations for adoption and sustainability of gamification in STEM education, it is important to look at both research findings and practical use. Gamification already shows strong potential to improve student motivation, engagement, and learning results in many education contexts, including STEM. But for successful adoption and long-term use, several factors must be considered carefully.

First, the use of gamification in STEM must be based on clear theoretical background and supported by research evidence. Studies prove that gamification can make learning better by increasing engagement, encouraging goal setting, and giving recognition to students (Charkova, 2024; Wang et al., 2024; Yusri & Zainal, 2025). For example, gamification in primary schools has improved performance, motivation, and skills in subjects like language, mathematics, and science (Yusri & Zainal, 2025). At higher education level, gamified strategies have been used in engineering courses to teach sustainability and global issues, with good results (Jain et al., 2022). Still, to make gamification sustainable, it is necessary to conduct long-term studies that measure how it affects engagement and learning over time (Wang et al., 2024; Yusri & Zainal, 2025; Scurati et al., 2020).

Second, the application of gamification should match the specific needs and context of each institution. This means taking into account cultural background, education level, and availability of technology. For instance, a study with adolescents from Europe and Middle East showed that a gamified framework improved hydrogen literacy and sustainability awareness, proving the importance of adaptive and context-sensitive design (Kramar & Knez, 2025). Digital tools like augmented reality and mobile apps can also increase learning by offering interactive and immersive environments (Ma et al., 2023; Despeisse, 2018). But challenges must be addressed, such as digital inequality, lack of teacher training, and ethical concerns about collecting student data (Martín-Rodríguez & Madrigal-Cerezo, 2025).In short, for gamification in STEM education to be adopted and maintained, a full approach is needed. This should include strong theoretical support, real evidence from studies, and context-based practice. By focusing on these aspects, institutions can build effective policies for gamification use in STEM, improving student learning and preparing graduates with skills needed for the 21st century.

Conclusion

Gamification in STEM education shows strong potential to improve student interest, motivation, and achievement. Adding elements like points, badges, leaderboards, and challenge cards into lessons creates more interactive and exciting environments (Teemueangsa & Jedaman, 2021; Mustan, 2025; Al-Hafdi & Alhalafawy, 2024). These approaches are supported by learning theories such as social constructivism and complexity theory, which help in keeping students engaged and in improving knowledge retention (Lottering et al., 2023). Gamification also allows for more personalized learning, where activities and content can match the needs of individual learners, support growth mindset and building new skills step by step (Sawarkar et al., 2024). Even so, challenges remain in bringing gamification into professional education and in meeting the different needs of diverse students (Feng et al., 2024; Rabah et al., 2018). The chapter therefore underlines the importance of continued research and systematic approaches in designing and applying gamified activities (Baldeón et al., 2016; Toda et al., 2019). For teachers, using gamification requires knowledge of both game design and education goals. To be effective, gamification must connect learning outcomes with the right game mechanics, so students not only enjoy but also achieve their goals (Baldeón et al., 2016). Policymakers need to support training and resources that help teachers apply gamification successfully. This means giving access to platforms, tools, and training that can support gamified teaching (Toda et al., 2019; Dicheva et al., 2019). Other stakeholders, such as schools, universities, and technology developers, should work together to create frameworks that match the needs of STEM education. Partnerships and investment in research will help to solve challenges in gamification and make its benefits stronger (Shi et al., 2023; Yadav & Dixit, 2023).

The future of gamification in STEM looks very promising. It can change traditional teaching into more engaging and effective methods. With technology developing fast, gamification will become more advanced, using features such as artificial intelligence and virtual reality to make learning more immersive (Panthalookaran, 2018). When combined with new technologies, gamification can provide adaptive and personalized learning, preparing students for future jobs and skills (Wahab et al., 2024; Ibrahim et al., 2023). More research and development will give knowledge about long-term impacts and best practices, helping teachers to refine their use of gamification (Yusri & Zainal, 2025; Awad et al., 2023). In the end, gamification is a transformative approach for STEM education, offering new solutions to engage students, develop critical skills, and encourage lifelong learning (Tabolina et al., 2021)

Recommendation

Gamification in STEM education has shown strong potential to improve student engagement, motivation, and learning results. Research between 2020 and 2025 points out many aspects of gamification, including how it is applied, how effective it is, and the challenges faced. Gamification means adding game features such as points, leaderboards, badges, and challenges into learning activities to make the process more interactive and motivating (Feng et al., 2024; Chatzidaki et al., 2025; Yadav & Dixit, 2023). Studies confirm that gamification can raise student motivation and participation by giving a sense of success and healthy competition (Chatzidaki et al., 2025; Gaurina & Pavlin, 2025). One study with fifth-grade students using a gamified web app showed that points and leaderboards were very effective in motivating learners, while badges had less impact (Chatzidaki et al., 2025). Gamification also supports better performance and skill building in subjects such as mathematics, science, and engineering (Awad et al., 2023; Yusri & Zainal, 2025; Moreira Parrales et al., 2024).

Still, successful use of gamification in STEM needs careful planning.

Teachers' knowledge and beliefs are very important for success. A study on physics teachers in Croatia found that most of them had a basic understanding and positive view of gamification, but differences appeared by age, teaching experience, and school type. This shows the importance of professional development that fits teachers' backgrounds (Gaurina & Pavlin, 2025). At the same time, gamified activities must match the education goals and student needs. For example, STEM challenge cards let students test different components and devices, which makes the learning more active and hands-on (Mustan, 2025). However, there are also challenges like the need for continuous evaluation, possible negative impacts, and lack of research on long-term results (Chatzidaki et al., 2025; Yusri & Zainal, 2025; Gini et al., 2025).In conclusion, gamification is a promising way to make STEM education more engaging and effective, but its success depends on careful design and ongoing assessment that consider the diverse needs of both students and teachers.

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References

Adetunla, A., Akinlabi, E., Jen, T. C., Okokpujie, I. P., & Ajibade, S.-S. (2024). A review on the Challenges and Prospects in Harnessing Virtual Reality in Education. *International Conference on Science, Engineering and Business for Driving Sustainable Development Goals, SEB4SDG 2024*. https://doi.org/10.1109/SEB4SDG60871.2024.10630094

Al-Azawi, R., Albadi, A., Moghaddas, R., & Westlake, J. (2019). Exploring the Potential of Using Augmented Reality and Virtual Reality for STEM Education. In U. L., S. G., R.-G. S., & L. D. (Eds.), *Communications in Computer and Information Science* (Vol. 1011, pp. 36–44). Springer Verlag. https://doi.org/10.1007/978-3-030-20798-4_4

Al-Hafdi, F. S., & Alhalafawy, W. S. (2024). Ten Years of Gamification-Based Learning: A Bibliometric Analysis and Systematic Review. *International Journal of Interactive Mobile Technologies*, *18*(7), 188–212. https://doi.org/10.3991/ijim.v18i07.45335

Al-Kfairy, M., Alfandi, O., Sharma, R. S., & Alrabaee, S. (2025). Digital Transformation of Education: An Integrated Framework for Metaverse, Blockchain, and AI-Driven Learning. In du B. B., D. M. T., T. E., & M. C. (Eds.), *International Conference on Computer Supported Education, CSEDU - Proceedings* (Vol. 1, pp. 865–873). Science and Technology Publications, Lda. https://doi.org/10.5220/0013499400003932

Alexandrovna, B. M., Semyonovich, B. V, Vladimirovna, B. I., & Pavlovna, S. Y. (2024). Developing digital technology for educational purposes. In A. A., A. G., S. R., B. V.S., O.-A. I.J., & S. M. (Eds.), *AIP Conference Proceedings* (Vol. 2816, Issue 1). American Institute of Physics. https://doi.org/10.1063/5.0177723

Andrade, P., Law, E. L.-C., Farah, J. C., & Gillet, D. (2020). Evaluating the Effects of Introducing Three Gamification Elements in STEM Educational Software for Secondary Schools. In A. N., L. T., P. B., P. C., W. S., M. D., L. L., & T. M. (Eds.), *ACM International Conference Proceeding Series* (pp. 220–232). Association for Computing Machinery. https://doi.org/10.1145/3441000.3441073

Aravind, K. A., Ranjan, R., Anusuya, M., Bhoopathy, V., Pathak, D. N., Goswami, A., & Babu, K. K. (2025). Role of AI in nuclear medicine training and education. In *AI Insights on Nuclear Medicine* (pp. 333–354). IGI Global. https://doi.org/10.4018/979-8-3373-1275-0.ch016

Ashley, M. S. (2025). Empowering STEM education: Harnessing magicschool AI for experiential learning. In *Harnessing AI's Potential to Support Student Success and Teaching Excellence* (pp. 51–107). IGI Global. https://doi.org/10.4018/979-8-3373-1122-7.ch003

Awad, M., Salameh, K., Redhaei, A. A., & Fraihat, S. (2023). Utilisation of gamification in higher education: a quick reference. *Global Journal of Engineering Education*, *25*(3), 177–182. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85176799610&partnerID=40&md5=70626ac4a24247cdd5fe8c4a809879c2

Badea, G., & Popescu, E. (2024). Integrating a Comprehensive Gamification Model in a Peer Assessment Platform. In B. L.-F. (Ed.), *2024 28th International Conference on System Theory, Control and Computing, ICSTCC 2024 - Proceedings* (pp. 385–390). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ICSTCC62912.2024.10744765

Balaskas, S., Zotos, C., Koutroumani, M., & Rigou, M. (2023). Effectiveness of GBL in the Engagement, Motivation, and Satisfaction of 6th Grade Pupils: A Kahoot! Approach. *Education Sciences*, *13*(12). https://doi.org/10.3390/educsci13121214

Baldeón, J., Rodríguez, I., & Puig, A. (2016). LEGA: A LEarner-centered GAmification design framework. In G.-P. F.J., P. V.M.R., de la R. C. E.J., & L. L.M. (Eds.), *ACM International Conference Proceeding Series*. Association for Computing Machinery. https://doi.org/10.1145/2998626.2998673

Banerjee, S., Banerjee, R., Gulati, C., & Chauhan, A. S. (2024). Gamification: An Emerging Educational Technology for Student Learning. *Proceedings of 2024 2nd International Conference on Recent Trends in Microelectronics, Automation, Computing, and Communications Systems: Exploration and Blend of Emerging Technologies for Future Innovation, ICMACC 2024*, 346–352. https://doi.org/10.1109/ICMACC62921.2024.10894409

Bennani, S., Maalel, A., & Ben Ghezala, H. (2022). Adaptive gamification in E-learning: A literature review and future challenges. *Computer Applications in Engineering Education*, *30*(2), 628–642. https://doi.org/10.1002/cae.22477

Bontchev, B., Terzieva, V., & Paunova-Hubenova, E. (2024). TEACHING STEM – ASPECTS OF PERSONALIZATION. *Lnternational Journal of Differential Equations and Applications*, *23*(1), 97–104. https://doi.org/10.12732/ijdea.v23i1.8

Borges, S. S., Mizoguchi, R., Durelli, V. H. S., Bittencourt, I. I., & Isotani, S. (2016). A link between worlds: Towards a conceptual framework for bridging player and learner roles in gamified collaborative learning contexts. In K. F., G. C., K. F., G. C., P. T., & K. A. (Eds.), *Communications in Computer and Information Science* (Vol. 677, pp. 19–34). Springer Verlag. https://doi.org/10.1007/978-3-319-52039-1_2

Bugri, V. A., & Egala, S. B. (2025). AI-Powered Innovation: Navigating the

Entrepreneurial Landscape in STEM Education. In *AI and Society: Navigating Policy, Ethics, and Innovation in a Transforming World* (pp. 23–50). Taylor and Francis. https://doi.org/10.4324/9781003595670-2

Bushuyev, S., Bushuyeva, N., Ilin, O., Murzabekova, S., Khussainova, M., & Saidullayev, R. (2025). Transformation of the education landscape in an AI environment. In I. A., K. K., & I. M. (Eds.), *CEUR Workshop Proceedings* (Vol. 3966). CEUR-WS. https://www.scopus.com/inward/record.uri?eid=2-s2.0-105006891106&partnerID=40&md5=567fc7186e93c7bd54883d89d361c3fc

Charkova, D. A. (2024). Utilizing gamification to promote pro-sustainable behavior among information technology students. *Discover Education*, *3*(1). https://doi.org/10.1007/s44217-024-00105-x

Chatzidaki, E., Doan, E. P. N., Kjelstrup, E. T., Papavlasopoulou, S., & Giannakos, M. (2025). Gamification in Informal Science Education: Enhancing Children's Motivation and Engagement with VitenChallenge Application. *IEEE Global Engineering Education Conference, EDUCON*. https://doi.org/10.1109/EDUCON62633.2025.11016487

Chumpanin, N., Jarupreechachan, W., & Attasena, V. (2024). "Dance of Notes" A fundamental Implication Design for a Music-Note Visualization Web-Application. *2024 13th International Conference on Educational and Information Technology, ICEIT 2024*, 111–116. https://doi.org/10.1109/ICEIT61397.2024.10540827

Chung, M. M. T., Leung, F., Wong, J. S. H., & Wong, T. M. (2025). Game-based learning in orthopaedics: A comprehensive review. *Journal of Clinical Orthopaedics and Trauma*, *67*. https://doi.org/10.1016/j.jcot.2025.103109

Dahalan, F., Alias, N., & Shaharom, M. S. N. (2024). Gamification and Game Based Learning for Vocational Education and Training: A Systematic Literature Review. *Education and Information Technologies*, *29*(2), 1279–1317. https://doi.org/10.1007/s10639-022-11548-w

Daud, R., Salam, S., Mohamad, S. N. M., & Yusoff, A. M. (2017). Modeling a mobile gamification model to increase student engagement: An analysis using analytic hierarchy process. *Advanced Science Letters*, *23*(9), 8707–8712. https://doi.org/10.1166/asl.2017.9955

Daungtod, S., & Chaijareon, S. (2019). A synthesis framework of constructivist via gamificationbased learning environments model to enhance self-regulation for undergraduate students. *ACM International Conference Proceeding Series*, 146–150. https://doi.org/10.1145/3306500.3306542

De Sousa Borges, S., Durelli, V. H. S., Reis, H. M., & Isotani, S. (2014). A systematic mapping on gamification applied to education. *Proceedings of the ACM Symposium on Applied Computing*, 216–222. https://doi.org/10.1145/2554850.2554956

Denden, M., Tlili, A., Essalmi, F., & Jemni, M. (2020). Students' learning performance in a gamified and self-determined learning environment. In K. S., B.-R. H., & S. S. (Eds.), *Proceedings of 2020 International Multi-Conference on: Organization of Knowledge and Advanced Technologies, OCTA 2020*. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/OCTA49274.2020.9151840

Despeisse, M. (2018). Teaching Sustainability Leadership in Manufacturing: A Reflection on the Educational Benefits of the Board Game Factory Heroes. In F. P., D. Y., L. A., O. S.I., B. N., N. M., & L. A. (Eds.), *Procedia CIRP* (Vol. 69, pp. 621–626). Elsevier B.V. https://doi.org/10.1016/j.procir.2017.11.130

Dicheva, D., Irwin, K., & Dichev, C. (2019). Exploring Learners Experience of Gamified Practicing: For Learning or for Fun? *International Journal of Serious Games*, *6*(3), 5–21. https://doi.org/10.17083/ijsg.v6i3.299

Dicheva, D., Irwin, K., & Dichev, C. (2023). A Software System to Support Student Engagement in Academic Courses. In R. A., F. C., & I. W. (Eds.), *Lecture Notes in Networks and Systems: Vol. 692 LNNS* (pp. 409–417). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-031-33261-6_35

Feng, J., Tan, W. H., & Yu, B. (2024). A systematic literature review of the impact of gamification instruction on students' problem-solving skills. *International Journal of Evaluation and Research in Education*, *13*(6), 4082–4092. https://doi.org/10.11591/ijere.v13i6.29695

Funa, A. A., Gabay, R. A. E., & Ricafort, J. D. (2021). GAMIFICATION IN GENETICS: EFFECTS OF GAMIFIED INSTRUCTIONAL MATERIALS ON THE STEM STUDENTS' INTRINSIC MOTIVATION. *Jurnal Pendidikan IPA Indonesia*, *10*(4), 462–473. https://doi.org/10.15294/jpii.v10i4.32143

Gaurina, M., & Pavlin, J. (2025). TEACHERS' KNOWLEDGE AND BELIEFS ABOUT GAMIFICATION IN PHYSICS CLASSROOMS. *Journal of Baltic Science Education*, *24*(2), 255–270. https://doi.org/10.33225/jbse/25.24.255

Giang, N. T., Dinh, N. V, Ngu, P. N. H., Chau, D. B., Thao, N. P., & Thao, T. T. P. (2025). Applying Augmented Reality Technology in STEM Education: A Bibliometrics Analysis in Scopus Database. *European Journal of Educational Research*, *14*(1), 73–87. https://doi.org/10.12973/eu-jer.14.1.73

Gini, F., Andrao, M., & Marconi, A. (2023). The SmartGame: mixing digital and tangible to foster math education and social interaction. *Proceedings of IDC 2023 - 22nd Annual ACM Interaction Design and Children Conference: Rediscovering Childhood*, 588–592. https://doi.org/10.1145/3585088.3593866

Gini, F., Bassanelli, S., Bonetti, F., Mogavi, R. H., Bucchiarione, A., & Marconi, A. (2025). The role and scope of gamification in education: A scientometric literature review. *Acta Psychologica*, *259*. https://doi.org/10.1016/j.actpsy.2025.105418

Guerra, A. R., de Medeiros, L. F., & Gericota, M. (2024). A Review of Immersivity in Distance Higher Education STEM Subjects. In B. M.-L., K. J.M., P. D., D. A., P.-R. A., & R. J. (Eds.), *Communications in Computer and Information Science: Vol. 1904 CCIS* (pp. 543–550). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-031-47328-9_39

Hajian, A., Daneshgar, S., Sadeghi R., K., Ojha, D., & Katiyar, G. (2024). From theory to practice: Empirical perspectives on the metaverse's potential. *Technological Forecasting and Social Change*, *201*. https://doi.org/10.1016/j.techfore.2024.123224

Huang, T.-C., & Tseng, H.-P. (2025). Extended Reality in Applied Sciences Education: A Systematic Review. *Applied Sciences (Switzerland)*, *15*(7). https://doi.org/10.3390/app15074038

Ibáñez, M.-B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers and Education*, *123*, 109–123. https://doi.org/10.1016/j.compedu.2018.05.002

Ibrahim, B., Rahman, S. A., Mohamad, N. H., & Shaari, N. (2023). Gamification of learning method in secondary school to enhance student performance. In A.-S. S.Z.S.I., M. W.A.W., W. M.H.A., & J. M.A. (Eds.), *AIP Conference Proceedings* (Vol. 2582, Issue 1). American Institute of Physics Inc. https://doi.org/10.1063/5.0130440

Jain, R., Joshi, R., Dwivedi, V., Senthil Kumar, G., & Badami, V. (2022). Gamification for Teaching Sustainability to Engineering Students. *Proceedings - Frontiers in Education Conference, FIE*, *2022-Octob*. https://doi.org/10.1109/FIE56618.2022.9962626

Jaskari, M.-M., & Syrjälä, H. (2024). One solution does not fit all: Reward-based and meaningful gamification in higher education. In *Practices and Implementation of Gamification in Higher Education* (pp. 22–49). IGI Global. https://doi.org/10.4018/979-8-3693-0716-8.ch002

Jindal, P., Singh, A., & Aggarwal, R. (2023). STEM: A multi-disciplinary approach to integrate pedagogies, inculcate innovations and connections. In *STEM: A Multi-Disciplinary Approach to Integrate Pedagogies, Inculcate Innovations and Connections*. Nova Science Publishers, Inc. https://doi.org/10.52305/UXLT2425

Jun, M., & Lucas, T. (2025). Gamification elements and their impacts on education: A review. *Multidisciplinary Reviews*, *8*(5). https://doi.org/10.31893/multirev.2025155

Kassenkhan, A. M., Moldagulova, A. N., & Serbin, V. V. (2025). Gamification and Artificial Intelligence in Education: A Review of Innovative Approaches to Fostering Critical Thinking. *IEEE Access*, *13*, 98699–98728. https://doi.org/10.1109/ACCESS.2025.3576147

Klock, A. C. T., Ogawa, A. N., Gasparini, I., & Pimenta, M. S. (2018). Does gamification matter?: A systematic mapping about the evaluation of gamification in educational environments. *Proceedings of the ACM Symposium on Applied Computing*, 2006–2012. https://doi.org/10.1145/3167132.3167347

Kok, C. L., Koh, Y. Y., Ho, C. K., Teo, T. H., & Lee, C. (2024). Enhancing Learning: Gamification and Immersive Experiences with AI. In L. B., S. S.K., L. Y.H., L. C.H.T., O. M., & A. A. (Eds.), *IEEE Region 10 Annual International Conference, Proceedings/TENCON* (pp. 1853–1856). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/TENCON61640.2024.10902870

Konca, A. S., Izci, B., & Simsar, A. (2024). Evaluating popular STEM applications for young children. *European Early Childhood Education Research Journal*, *32*(1), 130–146. https://doi.org/10.1080/1350293X.2023.2221414

Kononov, M., Kononova, N., Andrusenko, Y., Bagautdinova, A., & Mutsurova, Z. (2025). Augmented and Virtual Reality in Education. In L. M., P. G.S., & G. S. (Eds.), *Lecture Notes in Networks and Systems: Vol. 1222 LNNS* (pp. 304–312). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-031-78776-8_30

Kramar, U., & Knez, M. (2025). Gamified Learning for Sustainability: An Innovative Approach to Enhance Hydrogen Literacy and Environmental Awareness Through Simulation-Based Education. *Sustainability (Switzerland)*, *17*(6). https://doi.org/10.3390/su17062694

Kwok, B. W. J., Yeo, A., Wong, A., Loo, B. L. W., & Lee, J. S. A. (2023). Improving Immersive Virtual Reality Training of Bioreactor Operations using Gamification. *2023 IEEE International Conference on Teaching, Assessment and Learning for Engineering, TALE 2023 - Conference Proceedings*. https://

doi.org/10.1109/TALE56641.2023.10398406

Landers, R. N., Bauer, K. N., Callan, R. C., & Armstrong, M. B. (2015). Psychological theory and the gamification of learning. In *Gamification in Education and Business* (pp. 165–186). Springer International Publishing. https://doi.org/10.1007/978-3-319-10208-5_9

Leong, W. Y. (2025). Beyond the Screen: Enhancing Student Engagement in Virtual Classrooms Using Gamification. *2025 14th International Conference on Educational and Information Technology, ICEIT 2025*, 188–193. https://doi.org/10.1109/ICEIT64364.2025.10976109

Li, Z., & Edwards, S. H. (2020). Integrating role-playing gamification into programming activities to increase student engagement. *ASEE Annual Conference and Exposition, Conference Proceedings*, *2020-June*. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85095766142&partnerID=40&md5=b83b03177f5126547a224d7589fdc3a1

Logothetis, I., Barianos, A. K., Papadakis, A., Christinaki, E., Charalampakos, O., Katsaris, I., Kalogiannakis, M., & Vidakis, N. (2022). Gamification techniques capitalizing on state-of-the-art technologies. In *The Digital Folklore of Cyberculture and Digital Humanities* (pp. 206–229). IGI Global. https://doi.org/10.4018/978-1-6684-4461-0.ch012

López, V. M., Mon, M. Á. C., Gutiérrez, E. F., & González, A. D. (2022). Kahoot! As an innovative educational gamification proposal in Higher Education. *Digital Education Review*, *42*, 34–49. https://doi.org/10.1344/der.2022.42.34-49

Lottering, N., Lim, I., & Gough, S. (2023). Re-imagining health and medicine education: Implementing a mobile-based gamification app for improved affective learner engagement. In *Supporting Self-Regulated Learning and Student Success in Online Courses* (pp. 180–208). IGI Global. https://doi.org/10.4018/978-1-6684-6500-4.ch009

Lukita, C., Purnama, S., Rizky, A., & Fazri, M. F. (2024). Analysis of Gamification and Blockchain Integration in Intelligent Learning Systems. *2024 3rd International Conference on Creative Communication and Innovative Technology, ICCIT 2024*. https://doi.org/10.1109/ICCIT62134.2024.10701220

Ma, Y., Dik, N.-Y., & Fung, W. (2023). Turning Grey to Green: Engaging Gamification in Sustainability Education With Augmented Reality Technology. In S. T., B. G., & C. L. (Eds.), *Proceedings of the European Conference on Games-based Learning* (Vols. 2023-Octob, pp. 361–370). Dechema e.V. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85179004909&partner

ID=40&md5=59d53808d6ac6a0d4cd0d22da329260a

Martín-Rodríguez, A., & Madrigal-Cerezo, R. (2025). Technology-Enhanced Pedagogy in Physical Education: Bridging Engagement, Learning, and Lifelong Activity. *Education Sciences*, *15*(4). https://doi.org/10.3390/educsci15040409

Mitchell, D. L. (2025). AI and gamification engaging students in new ways. In *AI Applications and Pedagogical Innovation* (pp. 151–173). IGI Global. https://doi.org/10.4018/979-8-3373-5092-9.ch006

Momenipour, A., Pennathur, P. R., Pennathur, A., & Boswell, B. (2024). Board 127: Work in Progress: Strategizing the Integration of VR and AR in STEM Education: Aligning Educational, Organizational, and Technological Strategies. *ASEE Annual Conference and Exposition, Conference Proceedings*. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85202014115&partnerID=40&md5=b79b7652b1305e8de4948e761ce485ac

Moreira Parrales, M. L., Mejía Carrillo, M. J., Suarez Ibujes, M. O., & Torres Penafiel, J. S. (2024). Gamification for learning mathematics in secondary school: Most effective gamified strategies to motivate students and improve their performance in mathematics. *Salud, Ciencia y Tecnologia*, *4*. https://doi.org/10.56294/saludcyt20241016

Mustan, S. (2025). APPLICATION OF PROJECT-BASED LEARNING WITH GAMIFICATION USING STEM CARDS. *Mathematics and Education in Mathematics*, *54*, 150–157. https://doi.org/10.55630/mem.2025.54.150-157

Otemaier, K. R., Albuquerque, R., Diniz, R., Reinehr, S., & Malucelli, A. (2024). Immersive Role-Playing: An Experience Report on a Promising Approach to Learning Requirements Elicitation. *ACM International Conference Proceeding Series*, 586–595. https://doi.org/10.1145/3701625.3701683

Palomino, P. T., Rodrigues, L., & Toda, A. (2023). Gamification and motivation. In *Gamification Design for Educational Contexts: Theoretical and Practical Contributions* (pp. 15–35). Springer International Publishing. https://doi.org/10.1007/978-3-031-31949-5_2

Panthalookaran, V. (2018). Gamification of physics themes to nurture engineering professional and life skills. *IEEE Global Engineering Education Conference, EDUCON*, *2018-April*, 931–939. https://doi.org/10.1109/EDUCON.2018.8363330

Peng, S., Hong, D., & Huang, J. (2024). A Survey for Educational Metaverse: Advances and Beyond. In F. J. (Ed.), *Procedia Computer Science* (Vol. 246, Issue C, pp. 1456–1465). Elsevier B.V. https://doi.org/10.1016/j.procs.2024.09.590

Prieto Andreu, J. M. (2025). Systematic Review about Collaborative Learning in Virtual Reality, Augmented Reality and Mixed Reality. *Teoria de la Educacion*, *37*(1), 151–186. https://doi.org/10.14201/teri.31921

Rabah, J., Cassidy, R., & Beauchemin, R. (2018). Gamification in education: Real benefits or edutainment? In A. A., S. C., & N. K. (Eds.), *Proceedings of the European Conference on e-Learning, ECEL* (Vols. 2018-Novem, pp. 489–496). Academic Conferences Limited. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85057995444&partnerID=40&md5=36c506f7e76e5813a47b273cb06a9113

Ravi, R. V, Shinde, G., Roshini, T. V, & Aung, S. M. Y. (2023). Empowering future innovators: The importance of STEM education in today's world. In *STEM: A Multi-Disciplinary Approach to Integrate Pedagogies, Inculcate Innovations and Connections* (pp. 1–20). Nova Science Publishers, Inc. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85183483671&partnerID=40&md5=4cd238dc6813aa1b0fec994174e3e80e

Razzaq, A., Zhang, T., Numair, M., Alreshidi, A., Jing, C., Aljaloud, A., Ghayyur, S. A. K., Ahmed, S., & Qurat Ul Ain, M. (2024). Transforming academic assessment: The metaverse-backed Web 3 secure exam system. *Computer Applications in Engineering Education*, *32*(6). https://doi.org/10.1002/cae.22797

Rukadikar, A., & Khandelwal, K. (2025). Gamification at the workplace: a theoretical perspective on training and development. *Learning Organization*. https://doi.org/10.1108/TLO-07-2024-0239

Sangroya, D., & Kabra, G. (2023). Improving Students' Engagement using Gamification by Integrating Flow theory and Self Determination Theory. In R. D. & F. G. (Eds.), *AIP Conference Proceedings* (Vol. 2909, Issue 1). American Institute of Physics Inc. https://doi.org/10.1063/5.0181951

Sawarkar, D., Agrawal, P., Mandal, R. K., Pinjarkar, L., Agrawal, P., & Kaur, G. (2024). The Impact of Gamification Across Different Educational Contexts. *4th International Conference on Innovative Practices in Technology and Management 2024, ICIPTM 2024*. https://doi.org/10.1109/ICIPTM59628.2024.10563427

Schafer, H., Bachner, J., Pretscher, S., Groh, G., & Demetriou, Y. (2018). Study on motivating physical activity in children with personalized gamified feedback. *UMAP 2018 - Adjunct Publication of the 26th Conference on User Modeling, Adaptation and Personalization*, 221–226. https://doi.org/10.1145/3213586.3225227

Schaper, P., Riedmann, A., Semineth, M., & Lugrin, B. (2022). Addressing

Motivation in an E-Learning Scenario by applying Narration and Choice. In de Q. E., W. S.I., O. M., M. G., M. B., K. N., M. J., & R. J. (Eds.), *35th British HCI Conference Towards a Human-Centred Digital Society, HCI 2022*. BCS Learning and Development Ltd. https://doi.org/10.14236/ewic/HCI2022.18

Scurati, G. W., Ferrise, F., & Bertoni, M. (2020). Sustainability awareness in organizations through gamification and serious games: A systematic mapping. In M. N.H., H. C.T., & D. M. (Eds.), *Proceedings of the NordDesign 2020 Conference, NordDesign 2020*. The Design Society. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85094664228&partnerID=40&md5=bdc39c2e94db7e83c18e63c123efa3b5

Shi, Y., Horne, K. S., & Wu, Y. (2023). A Gamification Framework for Exploratory Learning in Higher STEM Education. *ASEE Annual Conference and Exposition, Conference Proceedings*. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85172101674&partnerID=40&md5=f633b1d75efc38f895eda35b6af985ec

Singh, M., & Sun, D. (2025). Evaluating Minecraft as a game-based metaverse platform: exploring gaming experience, social presence, and STEM outcomes. *Interactive Learning Environments*, *33*(7), 4272–4294. https://doi.org/10.1080/10494820.2025.2459200

Solano-Gonzales, N. D. C., Reyes-Burgos, K. C., Zelada-Valdivieso, H., & Mera-Montenegro, H. J. (2023). Gamification and programming: Enhancing mathematics learning in students. *Proceedings of the 2023 IEEE 3rd International Conference on Advanced Learning Technologies on Education and Research, ICALTER 2023*. https://doi.org/10.1109/ICALTER61411.2023.10372906

Son, J., Alhilal, A., Hadi Mogavi, R., Braud, T., & Hui, P. (2024). Making Learning Engaging and Productive: }SimLab, a VR Lab to Bridge Between Classroom Theory and Industrial Practice in Chemical Engineering Education. In F. X. (Ed.), *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics): Vol. 14730 LNCS* (pp. 160–179). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-031-60692-2_12

Sotirov, M., Petrova, V., & Nikolova-Sotirova, D. (2024). Enhancing Student Engagement Through Gamified Learning in Moodle LMS. *2024 23rd International Symposium on Electrical Apparatus and Technologies, SIELA 2024 - Proceedings*. https://doi.org/10.1109/SIELA61056.2024.10637857

Srimathi, S., & Anitha, D. (2025). Dynamic Horizon: AI and Gamification for Reshaping Higher Education. In *Adopting Artificial Intelligence Tools in*

Higher Education: Teaching and Learning (pp. 291–316). CRC Press. https://doi.org/10.1201/9781003469315-14

Studart, N. (2022). Gamification as a design instructional. *Revista Brasileira de Ensino de Fisica*, *44*. https://doi.org/10.1590/1806-9126-RBEF-2021-0362

Tabolina, A., Salkutsan, S., Kozlovskii, P., Popov, D., Kunina, O., Yudina, I., & Ryushenkova, A. (2021). Development and Implementation of Gamified Technologies in the Life Long Learning System (Based on a Multidisciplinary University). In A. M.E. & R. T. (Eds.), *Advances in Intelligent Systems and Computing: Vol. 1328 AISC* (pp. 510–516). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-030-68198-2_47

Teemueangsa, S., & Jedaman, P. (2021). Developing science learning activities using online gamification. In Y. C., N. N.D., B. A., S. H., W. I.S., & B. N.A. (Eds.), *Journal of Physics: Conference Series* (Vol. 1835, Issue 1). IOP Publishing Ltd. https://doi.org/10.1088/1742-6596/1835/1/012079

Teerawongpairoj, C., Tantipoj, C., & Sipiyaruk, K. (2024). The design and evaluation of gamified online role-play as a telehealth training strategy in dental education: an explanatory sequential mixed-methods study. *Scientific Reports*, *14*(1). https://doi.org/10.1038/s41598-024-58425-9

Tene, T., Marcatoma Tixi, J. A., Palacios Robalino, M. D. L., Mendoza Salazar, M. J., Vacacela Gomez, C., & Bellucci, S. (2024). Integrating immersive technologies with STEM education: a systematic review. *Frontiers in Education*, *9*. https://doi.org/10.3389/feduc.2024.1410163

Tian, S. (2024). The Integration of Computational Thinking and Artificial Intelligence Serves to Enhance The Cognitive Processes and Skill Acquisition of Students. *ACM International Conference Proceeding Series*, 564–567. https://doi.org/10.1145/3700297.3700394

Tjahjono, B., Soleman, M. D., Azmi, A., Millah, S., Andriani, R., & Dewi, E. R. (2022). Opportunities and Conditions in Education on Blockchain Gamification Technology. *2022 IEEE Creative Communication and Innovative Technology, ICCIT 2022*. https://doi.org/10.1109/ICCIT55355.2022.10118611

Toda, A. M., do Carmo, R. M. C., da Silva, A. P., Bittencourt, I. I., & Isotani, S. (2019). An approach for planning and deploying gamification concepts with social networks within educational contexts. *International Journal of Information Management*, *46*, 294–303. https://doi.org/10.1016/j.ijinfomgt.2018.10.001

Vasbieva, D. G., & Kalugina, O. A. (2024). Gamification Integration into Multilingual Classrooms. *XLinguae*, *17*(2), 178–189. https://doi.org/10.18355/XL.2024.17.02.12

Velazquez-Garcia, L., Cedillo-Hernandez, A., Longar-Blanco, M. D. P., & Bustos-Farias, E. (2025). Enhancing Educational Gamification through AI in Higher Education. *Proceedings of the 2024 the 16th International Conference on Education Technology and Computers, ICETC 2024*, 213–218. https://doi.org/10.1145/3702163.3702416

Vrcelj, A., Hoić-Božić, N., & Dlab, M. H. (2023). Use of Gamification in Primary and Secondary Education: A Systematic Literature Review. *International Journal of Educational Methodology*, *9*(1), 13–27. https://doi.org/10.12973/ijem.9.1.13

Wahab, N. A., Rosli, A. H., Mansoor, S. B. R. S., Jamaludin, N. A., & Adam, S. H. (2024). Leveraging Gamification for Engaged Learning in Online Teaching and Learning Experiences. In *Lecture Notes on Data Engineering and Communications Technologies* (Vol. 191, pp. 149–160). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-981-97-0293-0_11

Wang, Z., Harun, J., & Yuan, Y. (2024). ENHANCING READING INSTRUCTION THROUGH GAMIFICATION: A SYSTEMATIC REVIEW OF THEORETICAL MODELS, IMPLEMENTATION STRATEGIES, AND MEASURABLE OUTCOMES (2020–2024). *Journal of Information Technology Education: Research*, *23*, 1–27. https://doi.org/10.28945/5394

Yadav, S., & Dixit, S. (2023). Emerging pedagogy of gamification: A bibliometric study. In *Advanced Learning and Teaching in Higher Education in India: A Policy-technology-capacity Enabled Approach* (pp. 127–137). River Publishers. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85182287164&partnerID=40&md5=000dbe395b152e72ded9986e8347d544

Yeh, M. K.-C., Toshtzar, A., Guertin, L., & Yan, Y. (2016). Using spaced repetition and gamification to enhance K-12 student science literacy with on-demand mobile short reads. *Proceedings - Frontiers in Education Conference, FIE*, *2016-Novem*. https://doi.org/10.1109/FIE.2016.7757361

Yusri, A. A., & Zainal, M. Z. (2025). Unleashing gamification: a systematic review in primary schools. *Journal of Education and Learning*, *19*(4), 2313–2321. https://doi.org/10.11591/edulearn.v19i4.22009

Zabala-Vargas, S., García-Mora, L., Arciniegas-Hernández, E., Reina-Medrano, J., de Benito-Crosetti, B., & Darder-Mésquida, A. (2021). Strengthening Motivation in the Mathematical Engineering Teaching

Processes – A Proposal from Gamification and Game-Based Learning. *International Journal of Emerging Technologies in Learning*, *16*(6), 4–19. https://doi.org/10.3991/ijet.v16i06.16163

Zheng, E., & Wang, Q. (2023). Effectiveness of Online Collaborative Learning in Gamified Environments. *International Journal of Emerging Technologies in Learning*, *18*(17), 33–44. https://doi.org/10.3991/ijet.v18i17.42851

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Two Decades of Game-Based Learning Research in STEM Education

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Chapter Highlights

The following highlights summarise the research landscape, growth trends, and thematic structure of game-based learning in STEM education, highlighting key developments, dominant research themes, and emerging directions, while providing evidence-based insights to inform research, educational practice, and policy decisions.

- Presents a comprehensive bibliometric analysis of 407 publications on game-based learning in STEM education (GBL-STEM) published between 2006 and March 2025, revealing a rapid annual growth rate of 16.43% in the field.
- Identifies the United States as the leading contributor in terms of publication output, with Education Sciences as the most active journal and Computers & Education as the most highly cited source in GBL-STEM research.
- Demonstrates the interdisciplinary and collaborative structure of GBL-STEM studies through analyses of key authors, institutions, influential publications, and frequently used keywords.
- Reveals five major research clusters via keyword co-occurrence network visualization, highlighting dominant themes and emerging research trends within the field.
- Provides practical implications and evidence-based insights for educators, researchers, policymakers, and stakeholders seeking to effectively integrate game-based learning into STEM education.

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Introduction

STEM education has gained global recognition as a crucial educational priority, drawing significant attention from educators and policymakers. It aims to equip students with essential twenty-first-century skills while addressing real-world challenges (Su & Yang, 2024; L. Sun et al., 2023; Takeuchi et al., 2020). Nowadays, many countries have integrated STEM education into their national strategies to drive reforms in all levels of education (Holmlund et al., 2018; Sırakaya & Sırakaya, 2022), ensuring that future generations are prepared to engage with technological and scientific advancements. However, despite its importance, the number of students pursuing STEM-related careers remains low (Vedrenne-Gutiérrez et al., 2024). Also, research indicates that many students lack motivation to engage with STEM subjects, with interest often declining as early as primary school (Hiğde & Aktamış, 2022; Potvin & Hasni, 2014; Takeuchi et al., 2020). This disinterest can result in students avoiding STEM disciplines in later educational stages, ultimately impacting workforce readiness (Sırakaya & Sırakaya, 2022; Takeuchi et al., 2020). Given these challenges, STEM education should evolve to foster student engagement (Holmlund et al., 2018; Naji et al., 2025; D. Sun et al., 2023), ensuring that learners develop the critical thinking and problem-solving skills necessary to navigate complex technological landscapes (Matindike & Ramdhany, 2024; Naji et al., 2025).

One major obstacle to STEM education is the traditional classroom setting, which often struggles to capture students' interest or provide hands-on learning experiences due to time and resource constraints (Holmlund et al., 2018). The abstract and complex nature of STEM disciplines further contributes to these difficulties (Sırakaya & Sırakaya, 2022; D. Sun et al., 2023; Winberg et al., 2019). To address these challenges, integrating digital games into STEM curricula has emerged as a promising solution (Moon et al., 2024; Stohlmann, 2023). Research has demonstrated that game-based learning (GBL) can enhance student motivation, and provide interactive opportunities for developing problem-solving skills (Hussein et al., 2025; Moon et al., 2024). By leveraging digital games, educators can create immersive and engaging STEM learning environments that better prepare students for future careers related to STEM disciplines (Arztmann et al., 2023; Zhan et al., 2024).

In recent years, GBL has gained prominence in STEM education due to its ability to create interactive and experiential learning environments (Hussein et al., 2025; L. Sun et al., 2023). The increasing accessibility of mobile devices has further expanded opportunities for students to engage with STEM subjects anytime and anywhere, particularly benefiting digital-native learners (Gao et al., 2020). Mobile games provide flexibility, allowing students to learn at their own pace while enhancing motivation, engagement, and academic achievement (Ilić et al., 2024; L. Sun et al., 2023; Tene et al., 2025; Videnovik et al., 2023). Educational games also offer a dynamic environment where students can practice problem-solving, develop critical thinking skills, and engage with real-world challenges in a simulated setting (Fante et al., 2024; Guan et al., 2024; Gui et al., 2023).

The adoption of GBL in STEM education has expanded due to its ability to provide personalized learning experiences and long-term knowledge retention (Hussein et al., 2025; L. Sun et al., 2023). By embedding educational content within games, GBL facilitates knowledge acquisition in an enjoyable and immersive manner (Arztmann et al., 2023; Tene et al., 2025; Videnovik et al., 2023). Research indicates that GBL supports student-centered learning by promoting active participation, increasing motivation, and making complex concepts more accessible (Kefalis & Skordoulis, 2025; Videnovik et al., 2023). GBL also fosters students' autonomy and social connectedness, contributing to improved their conceptual understanding and learning experiences (Arztmann et al., 2023; Kefalis & Skordoulis, 2025). Compared to traditional teaching methods, GBL provides rich instructional support and fosters STEM literacy (Arztmann et al., 2023; Fante et al., 2024; Gui et al., 2023), making it a promising pedagogical approach for 21st-century education. In other words, GBL serves as an effective method for improving students' comprehension of STEM principles. Hence, as research continues to highlight its benefits, GBL remains a valuable strategy for improving student engagement, motivation, and academic performance in STEM fields (Hussein et al., 2025; Stohlmann, 2023; L. Sun et al., 2023; Tene et al., 2025; Videnovik et al., 2023).

Although research on GBL has gained momentum, with a rising number of studies focusing on STEM education over the past decade, prior reviews have generally examined a limited number of documents (Arztmann et al., 2023; Gui et al., 2023; Kefalis & Skordoulis, 2025). These studies are often confined to specific educational levels and subject areas (Fante et al., 2024; M. C. Li & Tsai, 2013; Videnovik et al., 2023) and are restricted in their temporal scope (Gao et al., 2020; Ilić et al., 2024; Tene et al., 2025). Despite the increasing adoption of GBL in STEM education, a comprehensive bibliometric review that synthesizes recent developments in this field remains unavailable. Although the body of literature on GBL continues to expand, a holistic understanding of its contributions to STEM education across different academic levels is also still lacking. To address existing gaps in the literature, quantitatively evaluate research productivity and impact, and offer valuable insights to various stakeholders, this study aims to present a comprehensive overview of the current state of GBL in STEM education. This review distinguishes itself from previous studies in several ways. First, it specifically focuses on GBL within STEM education, differentiating it from broader analyses of GBL. Second, it encompasses research published from the emergence of the first relevant study in 2006 up to 2025, ensuring a comprehensive temporal coverage. Finally, to maintain academic rigor, this review exclusively includes peer-reviewed journal articles, guaranteeing the reliability and credibility of the analyzed literature.

The study seeks to guide future research and practical applications in this rapidly evolving field. The key contribution of this paper lies in its broad examination of GBL-STEM research trends. Furthermore, it identifies leading scholars and their contributions, highlights influential countries and institutions, and traces the field's development over the past two decades. This information can be particularly beneficial for researchers, enabling them to focus on the most prominent topics within the discipline.

Methodology

Design

This study employed bibliometric analysis to explore recent developments in research on game-based learning in STEM education (GBL-STEM). A combination of quantitative methods, such as performance analysis, and qualitative approaches, including co-authorship and co-occurrence analysis, was utilized (Donthu et al., 2021). The analysis was conducted using two software tools: VOSviewer (van Eck & Waltman, 2010) and Bibliometrix (Aria & Cuccurullo, 2017). Through quantitative analysis, this study provides a comprehensive assessment of GBL-STEM research using various bibliometric indicators. Meanwhile, qualitative analysis reveals the intellectual framework of the field, incorporating keyword analysis and trend exploration. This includes frequently occurring keywords, keyword mapping, temporal keyword trends, thematic network analysis, and thematic evaluation.

Database

The data for this study were collected from the Scopus database, which offers a substantial number of academic publications with rich citation data. Scopus serves as an integrated research database, enabling scholars to systematically explore and assess relevant literature (Elsevier, 2023).

After selecting the database, a set of relevant keywords was determined to efficiently search for studies aligned with the research scope. The search was conducted within the titles, abstracts, and author keywords of publications. The search string used in this study was: TITLE-ABS-KEY ((“game-based learning” OR “gamification” OR “gamified” OR “game-based” OR “gamify” OR “digital game” OR “video game” OR “mobile game” OR “educational game” OR “learning game” OR “serious game” OR “game*” OR “augmented reality” OR “virtual reality”) AND (“STEAM education” OR “STEM education” OR “Science, Technology, Engineering, and Mathematics”)).

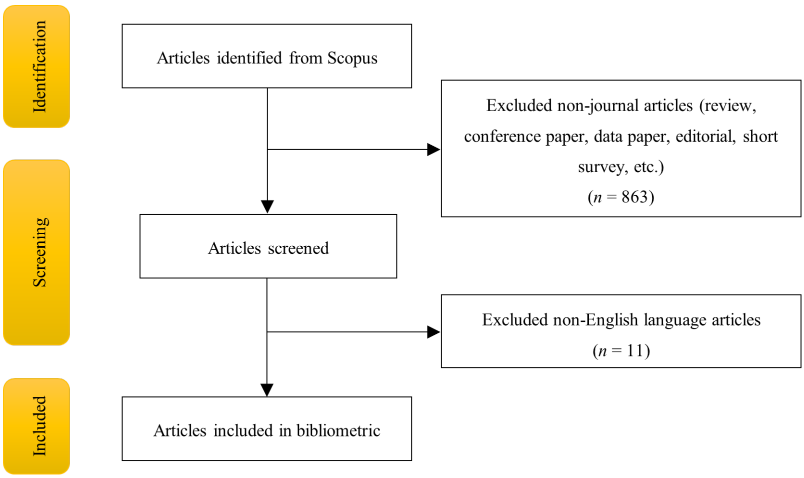

Figure 1. PRISMA diagram

To ensure a relevant dataset, the search was restricted to studies published between January 2006 and March 2025. Data extraction took place on March 22, 2025, yielding an initial dataset of 1,281 publications. The study focused exclusively on original research articles published in English, excluding review papers, conference proceedings, book chapters, comments, editorials, and letters. As of March 2025, 407 eligible articles were retrieved from Scopus and underwent a full-text analysis for bibliometric evaluation. The PRISMA protocol (Page et al., 2021) was followed to systematically assess the selected studies, as illustrated in Figure 1.

Inclusion and Exclusion Criteria

To systematically analyze the collected literature, specific inclusion and exclusion criteria were established. The inclusion criteria required that studies: (1) focus explicitly on GBL-STEM research, (2) be written in English, and (3) be published in peer-reviewed journals. Applying selective criteria for academic journals within this research domain ensures a manageable dataset while maintaining search quality. To uphold the study's methodological rigor, the following exclusion criteria were applied: (1) studies published in languages other than English, and (2) publications that do not belong to the category of journal articles.

Bibliometric Analysis

The bibliographic dataset was extracted from Scopus in .csv format for analysis. The Bibliometrix R package (Aria & Cuccurullo, 2017) was installed and performed to facilitate bibliometric assessment. Bibliometrix offers a range of analytical tools, enabling researchers to conduct a thorough bibliometric investigation. The .csv file was uploaded to the Biblioshiny interface for further processing. Additional data files in Excel (.csv) and image format (.png) were also obtained for analysis based on the study's objectives. In addition, VOSviewer was employed to generate and visualize bibliometric maps (van Eck & Waltman, 2010). Several bibliometric techniques were applied, including co-authorship and co-occurrence network analysis, to provide an in-depth examination of GBL-STEM research. Co-authorship analysis was used to map collaborative networks among researchers and countries. Furthermore, keyword co-occurrence analysis identified frequently associated terms within the same documents. Performance analysis was conducted to evaluate the contributions of various research entities—such as publications, journals, authors, institutions, and countries—to the GBL-STEM domain.

Results

Main Information

The research landscape on GBL-STEM has experienced significant growth over nearly two decades (Table 1). With a total of 407 documents published in 222 different journals, the field demonstrates a robust and expanding body of knowledge. The annual growth rate of 16.43% highlights the increasing interest and relevance of this research area, aligning with the broader trends in digital and interactive learning. The document average age of 4.29 years suggests that the field is relatively dynamic, with new findings frequently emerging. Additionally, an average of 22.04 citations per document indicates strong academic engagement and the impactful nature of these studies within the scientific community. The high number of keywords, both from keywords plus (1,242) and authors' keywords (1,183), reflects the diverse themes explored in GBL for STEM education.

Table 1. Preliminary information

Description	Results
Timespan	2006 to March 2025
Journals	222
Documents	407
Annual growth rate %	16.43
Document average age	4.29
Average citations per doc	22.04
Keywords plus	1242
Author's keywords	1183
Authors	1424
Authors of single-authored docs	37
Single-authored docs	37
Co-authors per doc	3.9
International co-authorships %	21.62

Authorship patterns also provide insights into research collaboration. A total of 1,424 authors contributed to these publications, with only 37 documents being single-authored. This suggests that research in this domain is predominantly collaborative, supported by the average of 3.9 co-authors per document. Furthermore, the international co-authorship rate of 21.62% highlights the global nature of GBL research, indicating cross-border academic cooperation and knowledge exchange. In conclusion, the study of GBL-STEM has seen substantial and continuous growth, with an increasing number of collaborative and widely cited publications. The expanding research network and high international co-authorship rate demonstrate the global interest in leveraging GBL for STEM education. Moving forward, this field is expected to evolve further, integrating emerging technologies and interdisciplinary approaches to enhance the effectiveness of STEM education through gamified learning experiences.

Trend in Scientific Production

The trend of research articles on GBL-STEM from 2006 to March 2025 demonstrates a significant increase in publication volume over time (Figure 2). According to Scopus, the number of articles remained relatively low from 2006 to 2014, with fewer than five articles per year. However, a notable rise began in 2015, reaching its peak in 2024 with 76 published articles. Despite this growing interest, the mean total citation per article exhibits a different pattern. The highest mean citation per article occurred in 2016 (82.82), followed by 2014 (64.67) and 2018 (54.20). These peaks suggest that the articles published in these years had a substantial impact on the academic community. However, from 2019 onward, the mean citation per article gradually declined, with a sharp drop observed in 2023 (8.79) and 2024 (2.47). The most recent data from 2025 shows an even lower citation count (0.44), which is expected as citations accumulate over time.

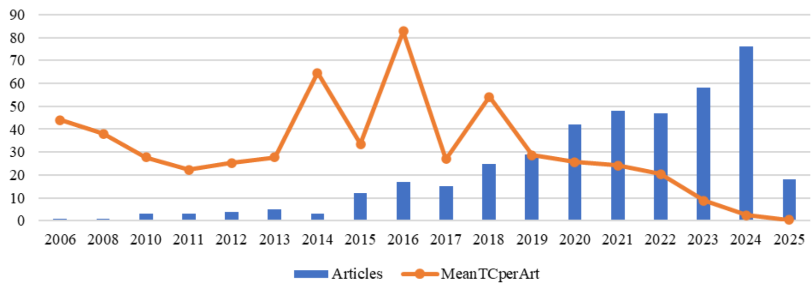

Figure 2. Publications and citations trends over time

The increase in publication volume in recent years may be attributed to the growing recognition of GBL as an effective approach in STEM education. While interest in GBL-STEM has grown exponentially, the citation impact of individual articles has diminished. This could be due to the longer time required for citations to accumulate.

Most Productive Authors

The analysis of the most prolific authors, those with the highest number of publications (NP) and total citations (TC) in GBL-STEM provides significant insights into the scholarly impact of this research field. Identifying leading authors in a specific field is crucial. Their publications serve as key references for the academic community. Table 2 and Figure 3 highlight the ten most influential authors who have made significant contributions to this area of study. Among the most productive authors, Lavicza, Z. from Johannes Kepler University Linz, Austria, leads with eight publications, followed by several authors with four contributions each, including Muntean, G.M., Muntean, C.H., Johnson-Glenberg, M.C., Jeong, J.S., and others. Lavicza, Z. published his first paper (FP) in 2021 titled "*Integrated STEAM approach in outdoor trails with elementary school pre-service teachers*" (Haas et al., 2021)we moved our on-campus STEAM (Science, Technology, Engineering, Arts and Mathematics in *Educational Technology and Society* (SJR: 1.56, Q1). Despite having fewer publications, some authors have achieved a substantial academic impact through citation counts and h-index (H), indicating the quality and influence of their work.

Table 2. Top 10 most productive authors

Author	NP	TC	H	Country	Institution	FP
Lavicza, Z.	8	94	18	Austria	Johannes Kepler University Linz	2021
Christopoulos, A.	4	237	14	Finland	University of Turku	2020
González-Gómez, D.	4	62	33	Spain	Universidad de Extremadura	2021
Jeong, J.S.	4	62	24	Spain	Universidad de Extremadura	2021
Johnson-Glenberg, M.C.	4	187	20	US	Arizona State University	2021
Muntean, C.H.	4	84	17	Ireland	National College of Ireland	2020
Muntean, G.M.	4	99	45	Ireland	Dublin City University	2020
Cotten, S.R.	3	96	40	US	Clemson University	2014
Din, R.	3	35	10	Malaysia	Universiti Kebangsaan Malaysia	2018
Fenyvesi, K.	3	39	7	Finland	University of Jyväskylä	2021

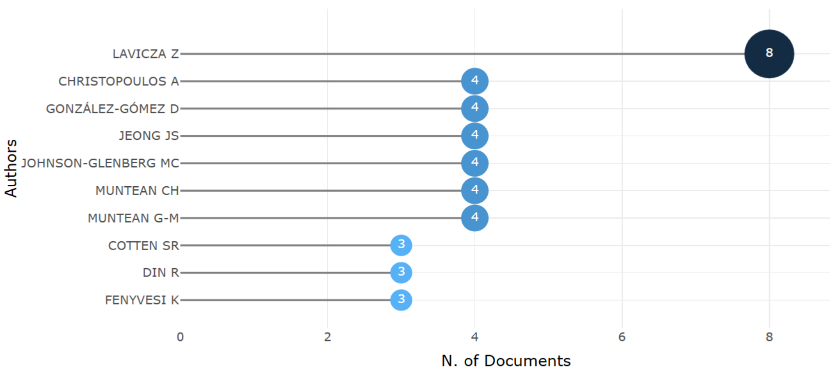

Figure 3. Most relevant authors

The highest total citation belongs to Christopoulos, A. from University of Turku (Finland) with 237 citations, demonstrating strong recognition of his work on learning analytics in virtual reality STEM applications. This is followed by Johnson-Glenberg, M.C. from Arizona State University (US) with 187 citations, whose research emphasizes embodied learning in STEM education, highlighting the importance of platform differences between 2D desktop and 3D virtual reality learning experiences. Muntean, G.M., from Dublin City University (Ireland), despite having only four publications, has garnered 99 citations, indicating a notable impact, particularly in the area of adventure-based 3D solar system games for primary school students. The highest h-index is attributed to Muntean, G.M. (45), followed by Cotten, S.R. (40) and González-Gómez, D. (33). The h-index serves as an indicator of consistent academic influence over time, suggesting that these scholars have produced high-quality work that has been frequently cited. Muntean, G.M. stands out as the most established researcher in this domain, with a strong academic footprint extending beyond game-based STEM education. Among the ten most prolific authors, Cotten, S.R. from Clemson University, US, was the first researcher to publish an article in this field. Her work revealed that the frequency of playing computer games was associated with higher self-efficacy in STEM. Geographically, the leading researchers are affiliated with institutions in Europe and the United States, with Austria, Ireland, Finland, Spain, and the US being prominent contributors. The presence of researchers from Johannes Kepler University Linz, Universidad de Extremadura, Dublin City University, and Arizona State University underscores the international interest in GBL within STEM.

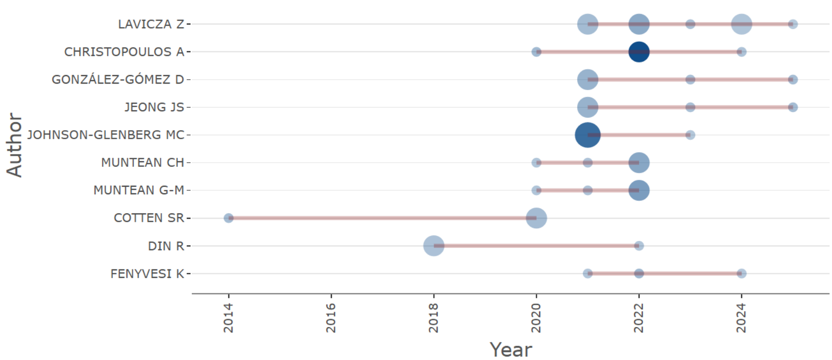

Figure 4. Authors' production over time

To present a comprehensive overview of the most influential authors in GBL-STEM research, taking into account their productivity trends over time, Figure 4 illustrates the total number of articles they have published from 2006 to 2025. The results illustrate the annual distribution of published papers, represented by circle dimensions, with each circle corresponding to an author's continuous publication activity. A larger circle signifies a higher number of articles published in a specific year, while a darker shade indicates a greater number of citations received within that period. Additionally, the connecting lines depict the duration of an author's publishing activity over time.

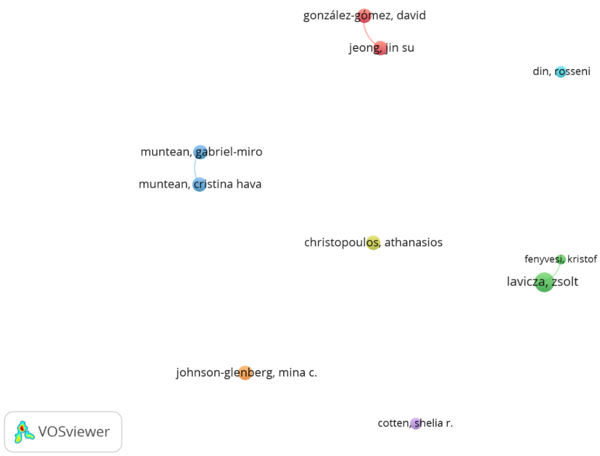

Figure 5. Authors' collaboration network of the top 10 most productive authors

The collaborations among the ten most productive authors are categorized into seven distinct clusters, indicating the presence of multiple research groups engaged in collaborative efforts. The size of each node represents the number of publications by an author, while the thickness of the connecting lines between two authors signifies the intensity of their collaboration (Figure 5). The figure reveals that the red (González-Gómez, D. and Jeong, J.S.), green (Lavicza, Z. and Fenyvesi, K.), and blue (Muntean, C.H. and Muntean, G.M.) clusters—each consisting of two authors—demonstrate a strong collaborative relationship. Meanwhile, the remaining four clusters comprise only a single author each. It indicates the need for greater collaboration among researchers worldwide in the field of GBL in STEM education.

Researchers exhibit varying levels of productivity in their scholarly output. This productivity can be analyzed using Lotka's law in bibliometrics, which estimates the scientific contribution of authors within the field of GBL-STEM. The findings, generated through Bibliometrix, are illustrated in Figure 6. The results indicate that a small proportion of authors are responsible for producing the majority of documents, whereas the number of publications decreases as the number of contributing authors per document increases. In summary, a limited number of authors generate a substantial portion of the publications, while the majority of authors contribute only a few documents. Specifically, 1,291 authors (90.7%) have authored only a single document on GBL-STEM, whereas only one author (0.10%) has contributed eight publications in this domain.

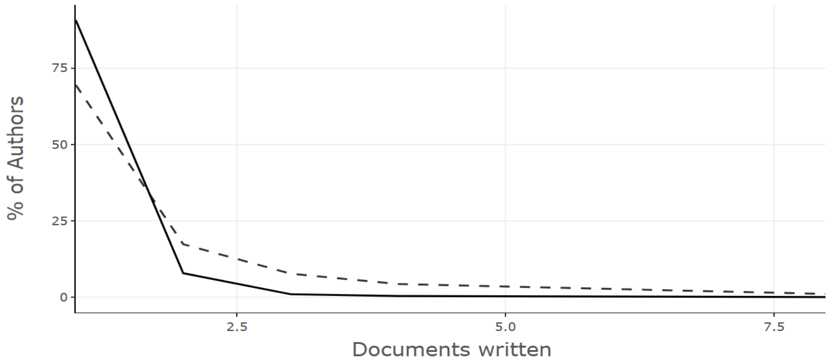

Figure 6. Author productivity through Lotka's law

Most Productive Countries

The analysis of GBL research in STEM education reveals significant contributions from various countries. The United States leads in the number of publications, with 149 papers, reflecting its strong research ecosystem and continuous advancements in this area. Despite its high publication count, the U.S. has an average article citation (AAC) of 24.91, suggesting widespread but moderately influential studies in this domain. The country's earliest contribution dates back to 2006 with Bhargava et al.'s (2006) study on a web-based virtual torsion laboratory, published in *Computer Applications in Engineering Education*, which laid the groundwork for subsequent research on GBL applications.

Spain, despite having only 30 publications, stands out with a remarkably high average article citation of 36.63, indicating that its contributions are highly influential within the academic community. The country's first significant paper in this field, conducted by Rodán et al. (2016)Technology, Engineering, and Mathematics and published in *Frontiers in Psychology* in 2016, examined how computerized mental rotation training influenced the visuospatial abilities of students aged 14 to 15 based on their experience with videogames to reduce the visuospatial gap between genders in STEM education. Malaysia has also made notable contributions, with 26 publications. However, its total citations (215) and average article citation (8.27) are relatively lower, suggesting that while research output is growing, the impact of its studies is not as extensive as in other leading countries.

Malaysia's first publication in 2015 by Sanmugam et al. (2015), which reviewed gamification as an educational tool, indicates the country's focus on motivational aspects in STEM education through GBL.

Table 3. Top 10 most productive countries

Country	NP	TC	AAC	FP
United States	149	3711	24.91	2006
Spain	30	1099	36.63	2016
Malaysia	26	215	8.27	2015
Taiwan	24	575	23.96	2015
United Kingdom	21	1013	48.24	2011
Australia	19	1075	56.58	2011
China	18	430	23.89	2015
Germany	15	268	17.87	2011
Singapore	12	210	17.50	2017
Canada	12	128	10.67	2015
Austria	12	872	72.67	2016

Beyond these three leading contributors, Austria stands out with the highest average article citation (72.67), despite having only 12 publications. This suggests that Austria's research, particularly Potkonjak et al.'s (2016) concepts such as distance learning, and open universities, are now becoming more widely used for teaching and learning. However, due to the nature of the subject domain, the teaching of Science, Technology, and Engineering are still relatively behind when using new technological approaches (particularly for online distance learning review on virtual laboratories in science, technology, and engineering education, published in *Computers and Education*, is exceptionally influential, possibly due to its comprehensive nature and broad applicability in STEM educational settings. Additionally, the United Kingdom and Australia exhibit strong citation performance, with average article citations of 48.24 and 56.58, respectively. Their early contributions in 2011 focused on virtual reality's role in education and immersive STEM experiences, underscoring the growing emphasis on interactive and experiential learning methods.

The collaborative relationships among the ten most prolific countries are categorized into three distinct clusters (Figure 7), comprising a total of 30 connections with an overall link strength of 51. In this network, the size of each node corresponds to a country's publication output, while the thickness of the connecting lines represents the strength of their research collaboration. The United States and Germany are both part of the blue cluster, signifying their prominent roles in fostering academic partnerships within this field. The United States, which has contributed 149 publications and accumulated 3,711 citations, maintains eight connections with a total link strength of 21, underscoring its extensive collaboration with other top ten nations. Meanwhile, Spain, positioned in the green cluster with 30 publications and 1,099 citations, has five connections and a total link strength of 8. The significant citation impact of the United States highlights its considerable influence on GBL-STEM research.

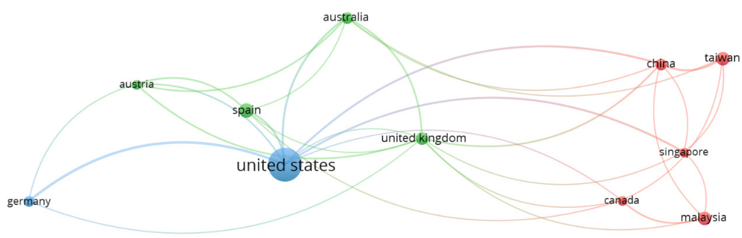

Figure 7. Country collaboration network of the top 10 most productive countries

Figure 8 indicates that over time, countries such as the United States, Spain, and Malaysia have made substantial contributions to research output. Notably, the United States has experienced a sharp rise in publications in recent years.

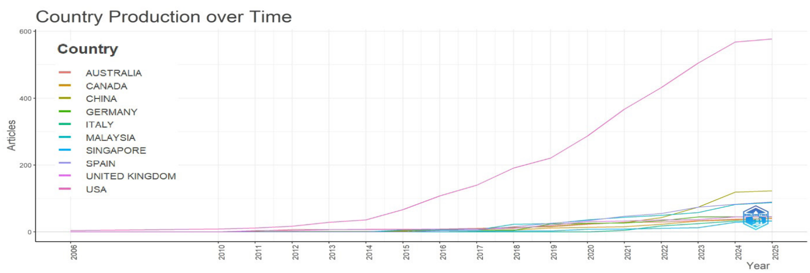

Figure 8. Countries' production over time

The three-field plot illustrates the connections between countries (left), author keywords (center), and journals (right) in GBL-STEM research. Larger rectangles signify elements with the highest number of relationships, while the thickness of the links represents the intensity of information flow between different values. Figure 9 presents Sankey diagrams depicting data from 10 countries, author keywords, and journals. The visualization highlights that researchers from the United States, China, Spain, and Malaysia have contributed significantly to shaping key research topics in GBL-STEM.

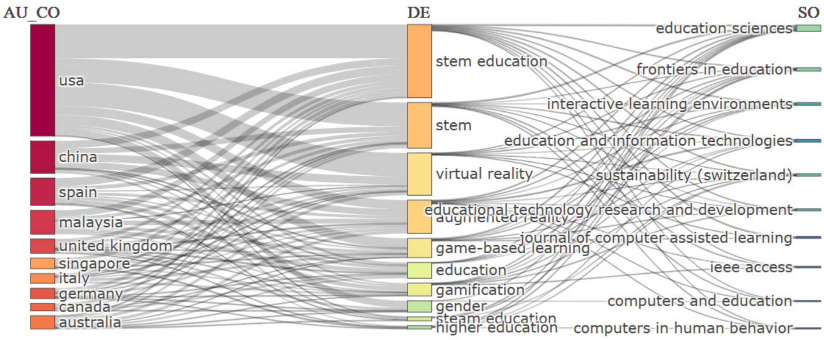

Figure 9. Three-field plot

It was found that countries with a higher volume of publications predominantly incorporated five key terms—STEM education, STEM, virtual reality, augmented reality, and game-based learning—highlighting their relevance in this field of study. The data further indicate that the United States is the leading contributor to nearly all of the top 10 keywords identified in the dataset. In addition to the US, China, Spain, and Malaysia also make significant contributions to publications associated with these keywords. Among these nations, the US demonstrates the most substantial influence on the keywords "STEM education," "STEM," and "virtual reality," though other countries also make notable contributions. Moreover, an analysis of the correlation between countries and academic journals reveals that publications from the US on "STEM education" and "augmented reality" are fairly distributed across various journals.

Most Productive Institutions

The research landscape on GBL-STEM has seen significant contributions from various institutions worldwide. Among them, Nanyang Technological University leads with ten publications, closely followed by Universiti Kebangsaan Malaysia with nine, and Arizona State University and Johannes Kepler University Linz with eight each. This indicates a strong commitment to GBL research in STEM education within these institutions, particularly in Southeast Asia, North America, and Central Europe.

Table 4. Top 10 most productive organizations

Institution	Country	NP	TC	AAC	FP
Nanyang Technological University	Singapore	10	191	19.10	2017
Universiti Kebangsaan Malaysia	Malaysia	9	111	12.33	2018
Arizona State University	US	8	447	55.88	2010
Johannes Kepler University Linz	Austria	8	94	11.75	2021
National Institute of Education	Singapore	7	180	25.71	2017
National Taiwan Normal University	Taiwan	7	301	43.00	2015
Michigan State University	US	7	211	30.14	2014
Pennsylvania State University	US	5	121	24.20	2020
NC State University	US	5	140	28.00	2014
Universidad de Extremadura	Spain	5	113	22.60	2020
University of Central Florida	US	5	95	19.00	2013
National College of Ireland	Ireland	5	84	16.80	2020

However, when considering total citations, a different trend emerges. Arizona State University has the highest total citation count (447), significantly surpassing other institutions. This suggests that its contributions have had a major impact on the academic discourse surrounding GBL in STEM. In contrast, Nanyang Technological University and Universiti Kebangsaan Malaysia have garnered 191 and 111 citations, respectively, reflecting a moderate but still influential presence in the field. A more refined metric, Average Article Citation (AAC), highlights the influence of individual publications. Arizona State University again stands out with the highest AAC (55.88), indicating that its research is not only widely recognized but also deeply influential. National Taiwan Normal University (Taiwan) follows closely with an impressive average citation count of 43.00, demonstrating strong academic engagement with its work. Michigan State University (US) also shows a high impact with an AAC of 30.14. These institutions have likely produced foundational studies that have shaped further research in game-based STEM learning.

The timeline of the first published articles from these institutions also provides insights into the evolution of this research area. Arizona State University published one of the earliest influential papers in 2010, titled A Next Gen Interface for Embodied Learning: SMALLab and the Geological Layer Cake, which appeared in the International Journal of Gaming and Computer-Mediated Simulations. This early contribution may have helped set the stage for subsequent studies. In contrast, Nanyang Technological

University and the National Institute of Education (both in Singapore) entered the field in 2017 with their research on problem-solving for STEM learning using games, while Universiti Kebangsaan Malaysia followed in 2018 with an augmented reality-based STEM learning approach. More recent contributions, such as those from Johannes Kepler University Linz (Austria) in 2021, indicate a continued and growing interest in integrating emerging technologies such as Augmented Reality and 3D Printing with GeoGebra in STEAM practices.

Most Relevant Journals

The research landscape on GBL-STEM reflects a growing interest across 222 academic journals, with notable contributions from different countries. Table 5 and Figure 10 present the top 10 active journals that published research in this field. When examining the number of publications, *Education Sciences* leads with 17 articles, followed by *Frontiers in Education* with 11 and *Sustainability Switzerland* with 10. These journals, particularly those published by MDPI, emphasize interdisciplinary approaches that integrate game-based strategies into STEM learning. The first recorded publication in this dataset appeared in 2011 in the *International Journal of Emerging Technologies in Learning*, discussing virtual reality as an educational tool.

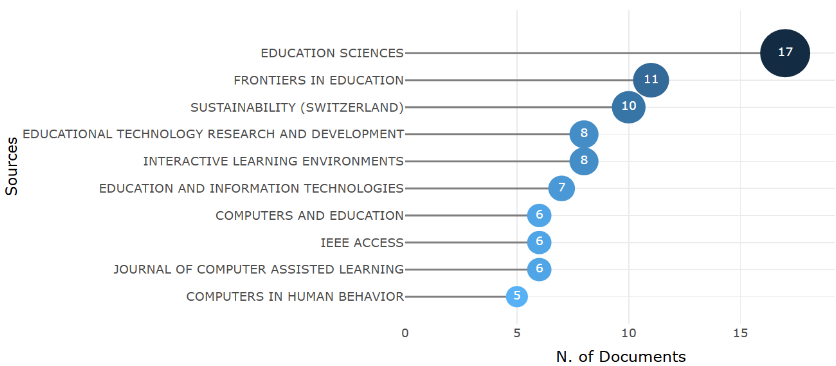

Figure 10. Most relevant sources

In terms of citation impact, *Computers and Education*, published by Elsevier, exhibits the highest total citation count (1149), underscoring its significant influence in the field. This is followed by *Educational Technology Research and Development* (329) and *Education Sciences* (319). The high citation numbers indicate the central role of technology integration in STEM learning and the sustained interest in understanding its impact on students' cognitive and affective development. Notably, the paper by Shank and

Cotten (2014)but little research has investigated the relationship between technology and empowerment for this population. We investigate how different aspects of technology use and ownership could empower urban youth through increasing their self-efficacy. Instead of simply a general measure of self-efficacy, we focus on several important domains related to STEM (Science, Technology, Engineering, and Mathematics in *Computers and Education* explores the empowering effect of technology on urban youth in STEM subjects, reflecting a broader interest in the intersection of technology, equity, and self-efficacy in education. *Computers and Education* also demonstrates the highest H-index (232), reinforcing its long-term impact in the field. Similarly, *IEEE Access* and *Computers in Human Behavior* also show strong academic recognition, with H-indices of 242 and 251, respectively. These values highlight the journals that have significantly shaped the research on game-based STEM learning. These journals are not only highly cited but also hold high SJR rankings, reflecting their prestige and rigorous peer-review processes.

Table 5. Top 10 most relevant sources

Journal	NP	TC	H	SJR(Q)	Publisher
Education Sciences	17	319	53	0.67(Q2)	MDPI
Frontiers in Education	11	87	40	0.63(Q2)	Frontiers Media S.A.
Sustainability Switzerland	10	167	169	0.67(Q1)	MDPI
Interactive Learning Environments	8	104	68	1.31(Q1)	Routledge
Educational Technology Research and Development	8	329	109	1.71(Q1)	Springer
Education and Information Technologies	7	267	76	1.30(Q1)	Springer
Journal of Computer Assisted Learning	6	389	114	1.84(Q1)	John Wiley and Sons
IEEE Access	6	70	242	0.96(Q1)	IEEE
Computers and Education	6	1149	232	3.65(Q1)	Elsevier
Journal of Science Education and Technology	5	245	80	1.60(Q1)	Springer
International Journal of Emerging Technologies in Learning	5	117	46	N/A	International Federation of Engineering Education Societies
Information Switzerland	5	146	59	0.70(Q2)	MDPI
IEEE Transactions on Education	5	169	76	0.79(Q1)	IEEE
Educational Technology and Society	5	184	111	1.56(Q1)	International Forum of Educational Technology and Society
Computers in Human Behavior	5	336	251	2.649Q1)	Elsevier

In terms of publishers, MDPI emerges as a major publisher in this domain, housing journals such as *Education Sciences, Sustainability Switzerland, and Information Switzerland*. This suggests a strong emphasis on open-access dissemination, making research more widely available. However, high-impact studies are more frequently published in well-established publishers such as Elsevier (*Computers and Education*, *Computers in Human Behavior*), Springer (*Education and Information Technologies*, *Journal of Science Education and Technology*), and Wiley (*Journal of Computer Assisted Learning*), indicating that these outlets attract research with sustained academic influence. The dominance of MDPI, Springer, Wiley, and Elsevier in this regard suggests that well-established publishers continue to shape the research on GBL in STEM.

Figure 11 illustrates the progression of top 10 journals over time, highlighting notable growth in *Education Sciences, Frontiers in Education,* and *Sustainability Switzerland*, particularly from 2017 onward. The *International Journal of Emerging Technologies in Learning* was the first to publish research on this topic in 2011. However, in recent years, *Education Sciences* has shown the most significant growth, with the number of publications in 2025 being four times higher than in 2020.

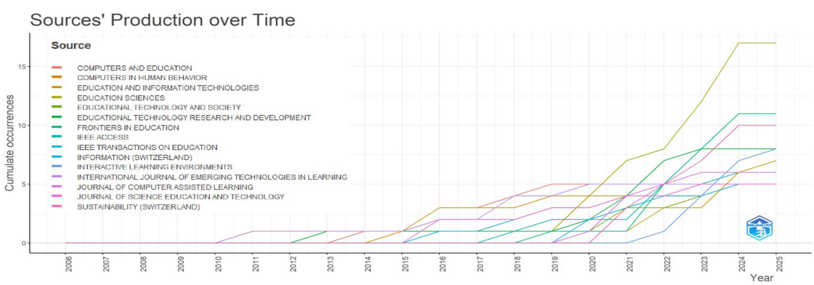

Figure 11. Sources' production over time

The distribution of document sources can be examined using Bradford's law, a bibliometric analysis principle. According to this law, the sources are categorized into three zones, with Zone 1 representing the core sources. These zones indicate the relative importance of sources within the studied field. As illustrated in Figure 12, the core zone consists of the most prolific sources. This figure highlights the primary sources, referring to the most prolific publication venues in the studied field. Within the core zone (Zone 1), a total of 22 journals were identified, accounting for 9.91% of the overall 222 journals analyzed. The most influential journal in this category is *Education Sciences*, which has published 17 articles and accumulated 319 citations. Meanwhile, Zone 2 comprises 66 journals, representing 29.73% of the total, while Zone 3 includes 134 journals, contributing 60.36% to the overall distribution.

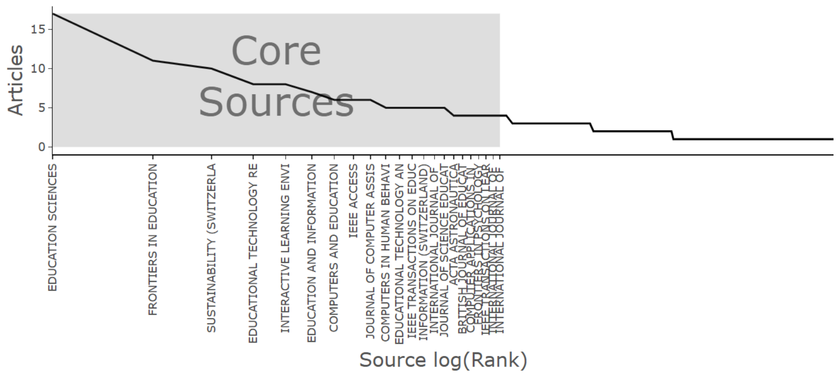

Figure 12. Bradford's law

Most Frequently Cited Manuscripts

Table 6 and Figure 13 present a detailed overview of the ten most highly cited journal articles, organized based on total citation count. Among the most influential works in this domain, three studies stand out based on the highest total citations, total citations per year, and overall impact on the field. One of the most cited studies is by Potkonjak et al. (2016)concepts such as distance learning, and open universities, are now becoming more widely used for teaching and learning. However, due to the nature of the subject domain, the teaching of Science, Technology, and Engineering are still relatively behind when using new technological approaches (particularly for online distance learning, titled "*Virtual laboratories for education in science, technology, and engineering: A review*," published in *Computers and Education*. With 677 citations and an annual citation rate of 67.70, this review paper systematically evaluates the role of virtual laboratories in STEM education. The study highlights the potential of virtual laboratories in supporting STEM learning. By synthesizing key technological advancements and pedagogical frameworks, this work has been foundational in shaping research and practice in digital laboratory simulations.

Table 6. Top 10 most cited documents

Author	DOI	Journal	TC	TCY
Potkonjak et al. (2016)	10.1016/j.compedu.2016.02.002	Comput. Educ.	677	67.70
Ibáñez & Delgado-Kloos (2018)	10.1016/j.compedu.2018.05.002	Comput. Educ.	609	76.13
Johnson-Glenberg (2018)	10.3389/frobt.2018.00081	Front. Robot. AI	236	29.50
Leonard et al. (2016)	10.1007/s10956-016-9628-2	J. Sci. Educ. Technol.	192	19.20
Aladé et al. (2016)	10.1016/j.chb.2016.03.080	Comput. Hum. Behav.	158	15.80
Mystakidis et al. (2022)	10.1007/s10639-021-10682-1	Educ. Inf. Technol.	147	36.75
Repenning et al. (2015)	10.1145/2700517	ACM J. Trans. Comput. Educ.	141	12.82
Lester et al. (2014)	10.1016/j.ins.2013.09.005	Inf. Sci.	122	10.17
Jesionkowska et al. (2020)	10.3390/educsci10080198	Educ. Sci.	118	19.67
Cooper et al. (2019)	10.1080/09523987.2019.1583461	Educ. Media. Int.	114	16.29

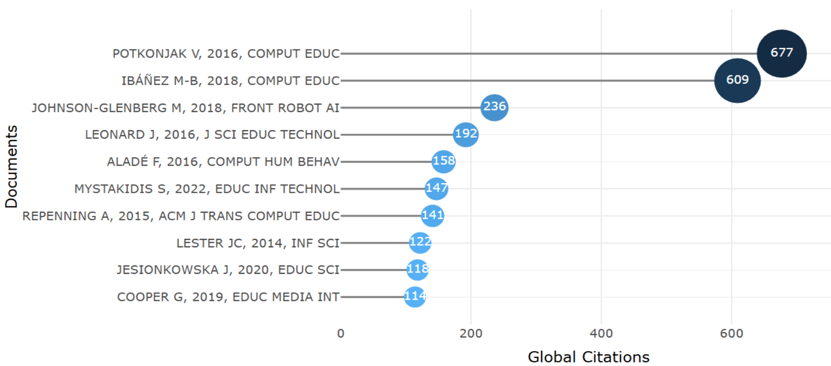

Figure 13. Top 10 most cited documents

Another highly influential study is by Ibáñez and Delgado-Kloos (2018), titled "*Augmented reality for STEM learning: A systematic review*," also published in *Computers and Education*. This paper surpasses Potkonjak et al. (2016)concepts such as distance learning, and open universities, are now becoming more widely used for teaching and learning. However, due to the nature of the subject domain, the teaching of Science, Technology, and Engineering are still relatively behind when using new technological approaches (particularly for online distance learning in terms of citation rate, with an impressive 76.13 citations per year and a total of 609 citations. Their review provides a comprehensive analysis of augmented reality (AR) applications in STEM education, emphasizing AR's potential to enhance conceptual understanding and affective learning outcomes. Johnson-Glenberg (2018) also made a significant contribution with the article "*Immersive VR and education: Embodied design principles that include gesture and hand controls*," published in *Frontiers in Robotics & AI*. While this paper has a lower total citation count (236), it stands out due to its high citation rate of 29.50 per year. This study focuses on the integration of virtual reality (VR) in STEM education, advocating for embodied learning through gesture-based interaction and hand controls. The paper provides empirical evidence on how VR environments can improve student engagement and retention by enabling active participation in STEM learning experiences. In terms of the most productive journal, *Computers and Education* emerges as a leading platform for research in game-based STEM learning. This journal has published two of the most highly cited articles in the dataset, reinforcing its reputation as a key venue for disseminating research on educational technology innovations.

Keywords Analysis

Figure 14 highlights the top 10 most commonly used author keywords. In this graph, the size of each keyword corresponds to its frequency of occurrence, with larger keywords appearing more frequently and smaller ones appearing less often. Among them, "STEM education" appears most frequently, with a total occurrence of 111 times. The second most frequent keyword is "STEM," which is mentioned 76 times, followed by "virtual reality," which appears 63 times.

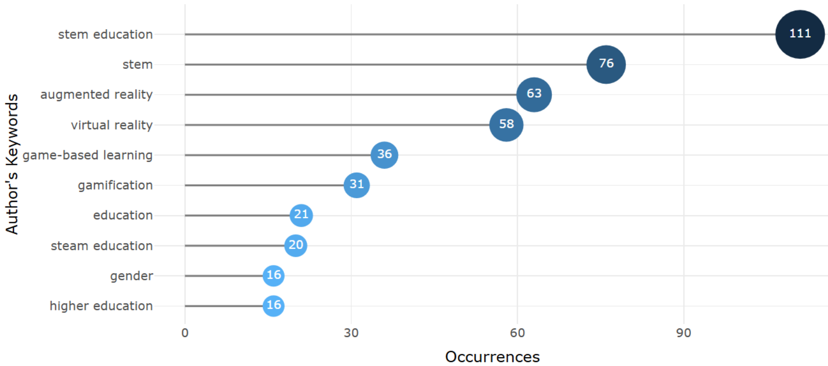

Figure 14. Most frequent words

Figure 15 displays a word cloud highlighting the most significant keyword combinations associated with GBL-STEM. This visualization displays the 50 most commonly appearing keywords in the analyzed documents, with "STEM Education" emerging as the most prevalent term. By leveraging this diagram, researchers can efficiently identify relevant studies based on keywords and analyze trends in the implementation of GBL within STEM education.

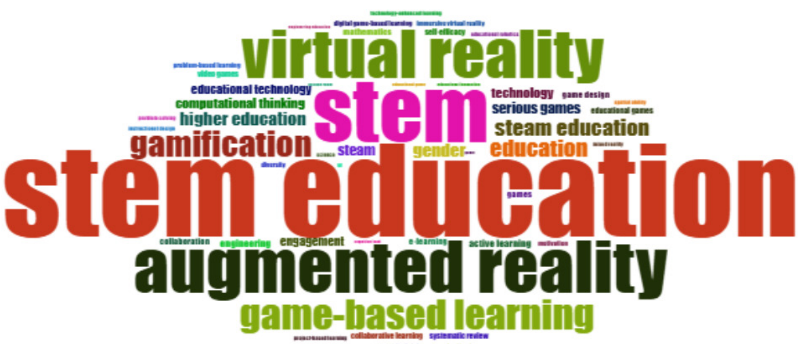

Figure 15. Word cloud by author keyword

Figure 16 presents the evolutionary trend of the author's keywords, with key milestones highlighted by the largest circles. The graph illustrates the thematic evolution of GBL-STEM research since its initial emergence in 2006. Notably, studies incorporating gamification, STEM, and education began to appear in 2021 and have shown a gradual upward trajectory, continuing to the present. Over time, an analysis of different periods allows us to identify the shifting research focus, particularly on the progressive exploration of GBL applications in STEM education.

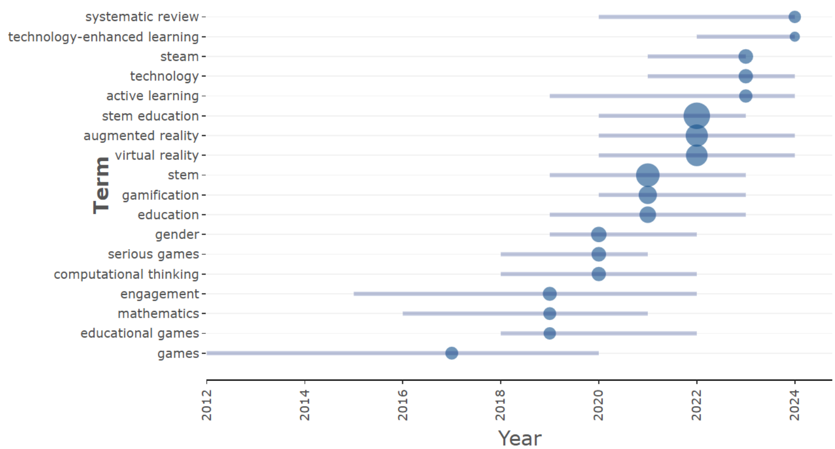

Figure 16. Trend topics of the GBL-STEM research

For the thematic evolution analysis, two cutoff points were selected, allowing us to generate a map of research interests across three distinct periods (Figure 17). During the first period (2006–2017), studies primarily focused on the integration of GBL and video games within STEM education, with an emphasis on game design and augmented reality to enhance educational experiences. Studies explored the potential of digital games as effective learning tools and investigated their impact on student engagement and knowledge acquisition. In the second period, between 2018 and 2021, the research focus shifted towards augmented reality and game design as innovative approaches to enhance learning motivation in STEM education. This period saw an increasing emphasis on interactive and immersive learning experiences that leverage games to improve student engagement and conceptual understanding. Between 2022 and 2025, recent research highlights the role of GBL and educational games in fostering learning motivation and engagement in STEM education. The integration of augmented reality continues to be a key focus, with studies exploring its potential to create more immersive and effective learning environments.

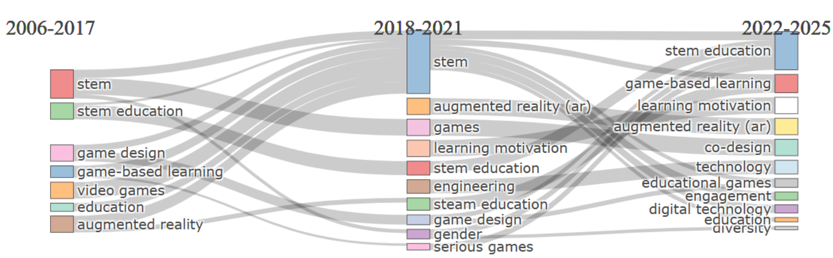

Figure 17. Thematic evolution of GBL-STEM research

Figure 18 illustrates the findings of the multiple correspondence analysis, highlighting a prominent red cluster that encompasses keywords such as "gamification," "augmented reality," and "educational technology." This clustering indicates a strong interrelation among these concepts.

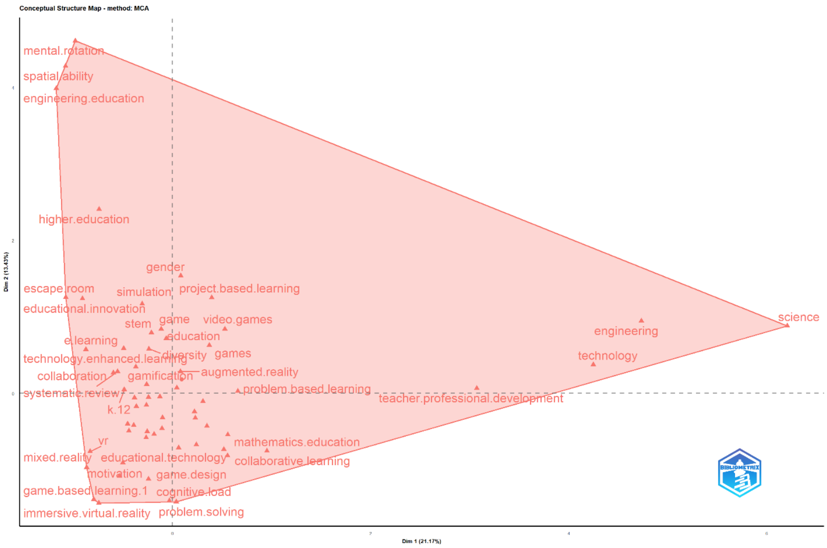

Figure 18. Multiple correspondences analysis

The thematic map is categorized into four distinct areas, each comprising four clusters arranged based on their density and centrality. These clusters consist of multiple keywords, as illustrated in Figure 19. The selection of the algorithm for keyword grouping determines both the number of clusters and their distribution within the thematic map. In this study, the Walktrap algorithm was applied. The results are visualized in four distinct quadrants, representing "motor themes," "niche themes," "emerging or declining themes," and "basic themes." This analysis seeks to explore and pinpoint relevant research topics from 2006 to 2025, highlighting shifts in themes and advancements in GBL within STEM education.

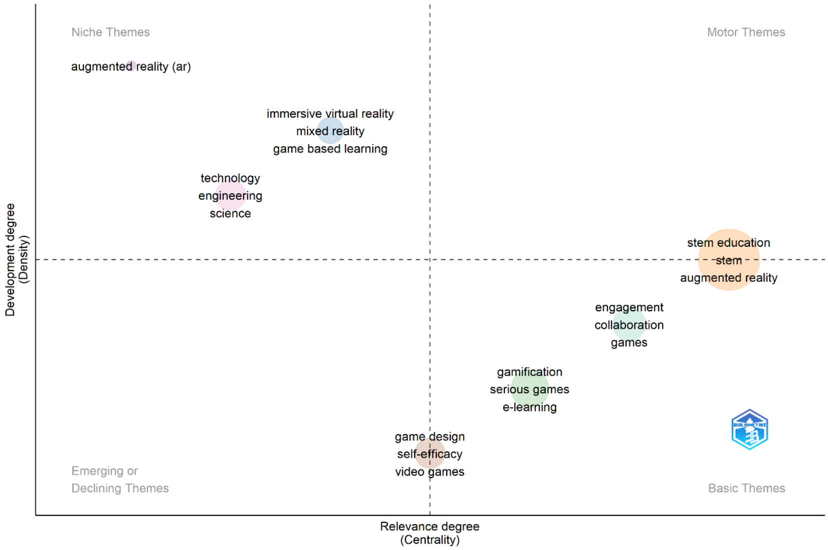

Figure 19. Thematic map for GBL-STEM research

- Motor themes: These themes (upper right quadrant) are both highly developed and central to the field, serving as fundamental drivers of research progress. Themes such as "STEM education", "STEM", and "augmented reality", remain essential yet continue to evolve in complexity and depth. Positioned between basic and motor themes, they highlight the diversity of ongoing research. For example, El Bedewy and Lavicza (2025) provided a comprehensive analysis of teacher professional development through GeoGebra visualization integrated with augmented reality. Their work is in line with the themes identified in this study, emphasizing the crucial role of AR games in STEM education.
- Niche themes: Although well-developed and specialized, these themes (upper left quadrant) have limited connections to the broader research landscape. Clusters such as "augmented reality", "virtual reality", "game-based learning", "technology", "engineering", and "science" are categorized as niche themes. For example, Singh and Sun (2025) explored the impact of GBL on STEM education, highlighting their role in enhancing empathetic engagement, minimizing negative social experiences, and fostering behavioral involvement among undergraduate and postgraduate students.
- Emerging or declining themes: Themes in this quadrant (lower left quadrant) exhibit low centrality and density, indicating either emerging research areas or those losing prominence. "Game design",

“self-efficacy”, and “video games” clusters are identified within this category, with their future trajectory depending on developments in the field. Ball et al. (2020) found that video game experience can influence STEM attitudes through the mediating role of computer self-efficacy. These themes, including “game design,” “self-efficacy,” and “video games,” have emerged as prominent research topics and are currently gaining increasing attention (Ortiz-Rojas et al., 2025; Petzel et al., 2024)progress towards gender parity in science, technology, engineering, and mathematics (STEM.

- Basic themes: These themes (lower right quadrant) are central to the research domain but remain underdeveloped, offering potential for further exploration. The “engagement”, “collaboration”, “games”, “gamification”, “serious games”, and “e-learning” clusters fall within this quadrant, signifying foundational yet evolving aspects of GBL-STEM research. In an empirical study, Wen (2021) examined the impact of augmented reality on learners’ cognitive engagement in language learning and recommended its use to enhance young learners’ involvement in the learning process.

The analysis of keyword co-occurrence plays a crucial role in identifying key research areas and provides a comprehensive overview of a research field, offering valuable insights into the topics explored and their interconnections. In this study, VOSviewer software was employed to perform a keyword co-occurrence analysis, as illustrated in Figure 20. The analysis was conducted using 407 documents retrieved from the Scopus database.

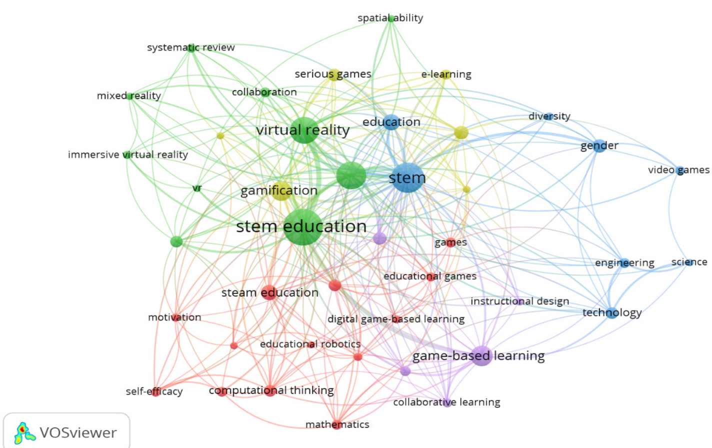

Figure 20. Co-occurrence of the author keywords

Figure 20 was generated by setting a minimum criterion of five keyword co-occurrences, which led to the identification of 42 keywords in total. These keywords were subsequently categorized into five distinct clusters—red, green, blue, yellow, and purple—illustrating their interconnections.

- Cluster 1 (13 items, red): *Engagement in STEAM Education* – focuses on the integration of STEAM education with game design to enhance student engagement and computational thinking through educational games. This cluster includes themes such as "STEAM education", "engagement", "computational thinking", "educational games", and "game design".
- Cluster 2 (10 items, green): *STEM Education and Emerging Technologies* – explores the role of augmented reality and virtual reality in STEM education, emphasizing the impact of educational technology on immersive and interactive learning experiences. The themes within this cluster include "STEM education", "augmented reality", virtual reality", and "educational technology".
- Cluster 3 (8 items, blue): *Gender Perspectives in STEM Education* – examines the intersection of STEM education, gender differences, and engineering through video games, highlighting inclusivity and representation in digital learning environments, covering topics such as "STEM", "gender", "education", "engineering", and "video games".
- Cluster 4 (6 items, yellow): *Gamification in Higher Education* – relates to the application of gamification and serious games in higher education, particularly within e-learning environments, to improve student motivation and learning outcomes. The themes associated with this cluster include "gamification", "serious games", "higher education", and "e-learning".
- Cluster 5 (5 items, purple): *Game-Based Learning in STEAM Education* – focuses on game-based learning approaches in STEAM education, emphasizing active and collaborative learning strategies to enhance student engagement and knowledge retention. This cluster includes concepts such as "game-based learning", "STEAM", "active learning", "instructional design", and "collaborative learning".

Figure 21 illustrates the evolving presence of key terms from January 2006 to March 2025, highlighting significant developments in GBL-STEM research. The analysis indicates that in 2011, the terms "augmented reality" and "virtual reality" appeared with relatively low frequency, suggesting that these topics received minimal attention at the time. However, their usage gradually increased over the years, reaching peak occurrences of

63 and 58, respectively, by 2025. This trend underscores the growing role of AR and VR games in STEM education. Furthermore, the terms “STEM education” and “STEM” have shown a marked rise in frequency, reflecting the expanding integration of STEM-related activities in educational settings. The increasing prominence of these keywords emphasizes the critical role of GBL in STEM instruction.

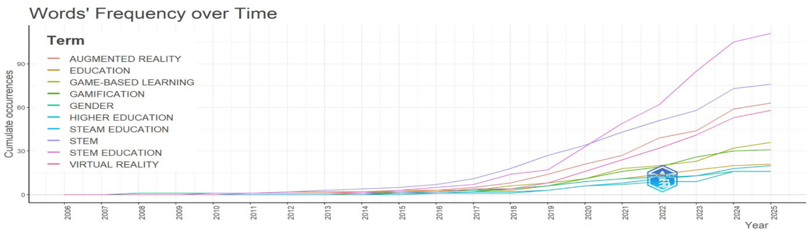

Figure 21. Words’ frequency over time

Conclusion

The research on GBL-STEM in the period 2006-2025 has shown a significant increase in the number of published articles over the years, particularly after 2015. This suggests a growing academic interest in the integration of GBL within STEM education. In general, while Lavicza, Z. is the most prolific author in terms of publication count, Christopoulos, A. and Johnson-Glenberg, M.C. have made substantial impacts through citation numbers, suggesting that their work resonates deeply within the academic community. Meanwhile, Muntean, G.M. emerges as a highly influential researcher with the highest h-index, indicating sustained contributions to the field. These findings highlight the evolving landscape of GBL-STEM, where both publication quantity and citation influence play critical roles in shaping research directions. Overall, the findings indicate that while the United States dominates in publication volume, European countries such as Spain, Austria, and the United Kingdom demonstrate higher research impact per article. Meanwhile, Asian nations, including Malaysia and Taiwan, show growing engagement in GBL research, contributing valuable perspectives on gamification and virtual learning environments. This trend underscores a global shift toward innovative, technology-driven STEM education methodologies, with significant variations in research influence across regions.

In terms of institutions, Nanyang Technological University (Singapore), Universiti Kebangsaan Malaysia (Malaysia), and Arizona State University (US) stand out as the top three institutions in terms of the number of publications. The data highlight that GBL-STEM has been a growing research focus globally, with particularly strong contributions from institutions in the US, Singapore, and Malaysia. While the number of publications provides an overview of research activity, citation metrics reveal the depth of impact these studies have had. Arizona State University emerges as a leading institution in terms of influence, whereas National Taiwan Normal University and Michigan State University also demonstrate strong academic engagement. The research trend suggests that early contributions from the 2010s laid the foundation for the field, with continued innovation and new approaches being explored in recent years. As technology evolves, the impact and scope of GBL-STEM are likely to expand further, integrating newer advancements such as virtual and augmented reality into pedagogical frameworks.

Among the journals with the highest number of publications, *Education Sciences* leads with 17 articles, followed by *Frontiers in Education* (11 articles) and *Sustainability Switzerland* (10 articles). While these journals have contributed the most studies, the highest total citations are observed in *Computers and Education* (1,149 citations across 6 articles), *Journal of Computer Assisted Learning* (389 citations across 6 articles), and *Educational Technology Research and Development* (329 citations across 8 articles). This discrepancy suggests that although some journals publish more frequently on the topic, others have greater academic influence, as indicated by higher citation rates. GBL-STEM has experienced substantial growth, with MDPI and Springer leading in publication volume, while Elsevier and Wiley maintain high citation influence. The most impactful studies appear in journals with strong citation records, suggesting that while quantity matters, the depth of contribution ultimately defines the field's trajectory.

In recent years, digital educational games have become increasingly prevalent, establishing GBL as a major trend in STEM education (Kefalis & Skordoulis, 2025; Tene et al., 2025). However, there remains no clear consensus among researchers regarding its effectiveness. The integration of mobile technology into educational games has expanded opportunities for personalized and flexible learning (Fante et al., 2024; Gao et al., 2020), allowing students to engage with STEM subjects anytime and anywhere (Gao et al., 2020; Tene et al., 2025). Compared to conventional teaching methods, GBL has demonstrated the potential to enhance student motivation and comprehension of STEM concepts (Fante et al., 2024; Videnovik et al., 2023). The growing presence of video games in students' lives has also encouraged educators to explore their use beyond entertainment, incorporating them into educational settings to improve learning outcomes (Arztmann et al., 2023; Gui et al., 2023; Tene et al., 2025).

Gamified learning environments have proven to be valuable in STEM education by simulating real-world scenarios, enabling students to apply theoretical knowledge in practical contexts (Kefalis & Skordoulis, 2025; Videnovik et al., 2023). This experiential approach enhances comprehension and fosters a deeper connection to STEM subjects (Fante et al., 2024; Ilić et al., 2024). By creating interactive and engaging learning spaces, educational games encourage active participation while promoting the development of critical thinking and problem-solving skills (Gao et al., 2020; Moon et al., 2024). As a result, GBL has been recognized as an effective strategy for achieving STEM education goals (Gui et al., 2023), helping students not only grasp theoretical content but also understand its real-world applications.

Numerous studies suggest that GBL positively impacts student achievement, motivation, and engagement (Gao et al., 2020; K. Li et al., 2023; Moon et al., 2024). In STEM education, digital games facilitate the exploration of complex scientific phenomena that may be difficult to observe in traditional learning environments (Fante et al., 2024). Additionally, digital games allow students to virtually explore otherwise inaccessible locations or conduct experiments in simulated environments (Moon et al., 2024). Furthermore, GBL offers structured guidance and contextual support (Kefalis & Skordoulis, 2025), fostering essential skills such as problem-solving (Tene et al., 2025; Videnovik et al., 2023), which are crucial for success in STEM fields. As research continues to highlight its benefits, GBL remains a promising pedagogical tool for enhancing STEM education (Ilić et al., 2024; Stohlmann, 2023; Tene et al., 2025).

This study has some limitations, primarily due to the exclusive use of Scopus-indexed papers, which may have led to the exclusion of relevant publications indexed elsewhere. Although Scopus is a widely recognized and reliable database, integrating it with other sources, such as Web of Science (WOS), could enable a more comprehensive bibliometric analysis. Future studies should consider expanding the data sources to gain a broader perspective on the GBL-STEM field. Additionally, this study focused solely on journal articles, omitting other types of publications such as books, reviews, etc. Despite these limitations, the findings offer valuable insights into the landscape of GBL-STEM research.

References

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, *11*(4), 959–975. https://doi.org/10.1016/j.joi.2017.08.007

Arztmann, M., Hornstra, L., Jeuring, J., & Kester, L. (2023). Effects of games in STEM education: A meta-analysis on the moderating role of student background characteristics. *Studies in Science Education*, *59*(1), 109–145. https://doi.org/10.1080/03057267.2022.2057732

Ball, C., Huang, K. T., Cotten, S. R., & Rikard, R. V. (2020). Gaming the SySTEM: The relationship between video games and the digital and STEM divides. *Games and Culture*, *15*(5), 501–528. https://doi.org/10.1177/1555412018812513

Bhargava, P., Antonakakis, J., Cunningham, C., & Zehnder, A. T. (2006). Web-based virtual torsion laboratory. *Computer Applications in Engineering Education*, *14*(1), 1–8. https://doi.org/10.1002/cae.20061

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, *133*, 285–296. https://doi.org/10.1016/j.jbusres.2021.04.070

El Bedewy, S., & Lavicza, Z. (2025). A STEAM experience: Architectural modeling and technology exploitation at the museum. *Journal of Museum Education*, 1–20. https://doi.org/10.1080/10598650.2024.2440288

Elsevier. (2023). *Content coverage guide*. https://assets.ctfassets.net/o78em1y1w4i4/EX1iy8VxBeQKf8aN2XzOp/c36f79db25484cb38a5972ad9a5472ec/Scopus_ContentCoverage_Guide_WEB.pdf

Fante, C., Ravicchio, F., & Manganello, F. (2024). Navigating the evolution of game-based educational approaches in secondary STEM education: A decade of innovations and challenges. *Education Sciences*, *14*(6). https://doi.org/10.3390/educsci14060662

Gao, F., Li, L., & Sun, Y. (2020). A systematic review of mobile game-based learning in STEM education. *Educational Technology Research and Development*, *68*(4), 1791–1827. https://doi.org/10.1007/s11423-020-09787-0

Guan, X., Sun, C., Hwang, G. jen, Xue, K., & Wang, Z. (2024). Applying game-based learning in primary education: A systematic review of journal publications from 2010 to 2020. *Interactive Learning Environments*, *32*(2), 534–556. https://doi.org/10.1080/10494820.2022.2091611

Gui, Y., Cai, Z., Yang, Y., Kong, L., Fan, X., & Tai, R. H. (2023). Effectiveness of digital educational game and game design in STEM learning: A meta-analytic review. *International Journal of STEM Education*, *10*(1). https://doi.org/10.1186/s40594-023-00424-9

Haas, B., Kreis, Y., & Lavicza, Z. (2021). Integrated STEAM approach in outdoor trails with elementary school pre-service teachers. *Educational Technology and Society*, *24*(4), 205–219.

Hiğde, E., & Aktamış, H. (2022). The effects of STEM activities on students' STEM career interests, motivation, science process skills, science achievement and views. *Thinking Skills and Creativity*, *43*, 101000. https://doi.org/10.1016/j.tsc.2022.101000

Holmlund, T. D., Lesseig, K., & Slavit, D. (2018). Making sense of "STEM education" in K-12 contexts. *International Journal of STEM Education*, *5*, 32.

Hussein, M. H., Sulaiman, N. L., Noroozi, O., Elaish, M. M., & Alhasan, A. (2025). Value-added digital game-based learning in K-12 science education: A systematic literature review. *Interactive Learning Environments*, 1–35. https://doi.org/10.1080/10494820.2025.2450652

Ibáñez, M. B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers and Education*, *123*, 109–123. https://doi.org/10.1016/j.compedu.2018.05.002

Ilić, J., Ivanović, M., & Klašnja-Milićević, A. (2024). Effects of digital game-based learning in STEM education on students' motivation: A systematic literature review. *Journal of Baltic Science Education*, *23*(1), 20–36. https://doi.org/10.33225/jbse/24.23.20

Johnson-Glenberg, M. (2018). Immersive VR and education: Embodied design principles that include gesture and hand controls. *Frontiers Robotics AI*, *5*, 81. https://doi.org/10.3389/frobt.2018.00081

Kefalis, C., & Skordoulis, C. (2025). Digital simulations in STEM education: Insights from recent empirical studies, A systematic review. *Encyclopedia*, *5*, 10. https://doi.org/https://doi.org/10.3390/encyclopedia5010010

Li, K., Peterson, M., Wang, Q., & Wang, H. (2023). Mapping the research trends of digital game-based language learning (DGBLL): A scientometrics review. *Computer Assisted Language Learning*. https://doi.org/10.1080/09588221.2023.2299436

Li, M. C., & Tsai, C. C. (2013). Game-based learning in science education: A review of relevant research. *Journal of Science Education and Technology*, *22*(6), 877–898. https://doi.org/10.1007/s10956-013-9436-x

Matindike, F., & Ramdhany, V. (2024). Incorporating indigenous knowledge perspectives in integrated STEM education: A systematic review. *Research in Science and Technological Education*, 1–21. https://doi.org/10.1080/02635143.2024.2413675

Moon, J., Yeo, S., Si, Q., & Ijeluola, A. S. (2024). A scoping review of game-based learning for mathematics teacher education. *International Journal of Mathematical Education in Science and Technology*. https://doi.org/10.1080/0020739X.2024.2337934

Naji, K. K., Al-Ali, A., Ayari, M. A., Santhosh, M. E., Naji, A. K. K., & Al-Hazbi, S. M. A. (2025). Virtual frontiers in STEM education: A systematic review and SWOT analysis of virtual reality-based interventions at the preparatory school level. *Computers in the Schools*, 1–23. https://doi.org/10.1080/07380569.2025.2472684

Ortiz-Rojas, M., Chiluiza, K., Valcke, M., & Bolanos-Mendoza, C. (2025). How gamification boosts learning in STEM higher education: A mixed methods study. *International Journal of STEM Education*, *12*, 1. https://doi.org/10.1186/s40594-024-00521-3

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *The BMJ*, *372*. https://doi.org/10.1136/bmj.n71

Petzel, Z. W., Farrell, L., McCormack, T., Turner, R. N., Rafferty, K., & Latu, I. M. (2024). A collective action approach to improving attitudes and self-efficacy towards gender equality among male STEM academics. *European Journal of Psychology of Education*, *39*(3), 3161–3184. https://doi.org/10.1007/s10212-024-00844-3

Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers and Education*, *95*, 309–327. https://doi.org/10.1016/j.compedu.2016.02.002

Potvin, P., & Hasni, A. (2014). Analysis of the decline in interest towards school science and technology from grades 5 through 11. *Journal of Science Education and Technology*, *23*(6), 784–802. https://doi.org/10.1007/s10956-014-9512-x

Rodán, A., Contreras, M. J., Rosa Elosúa, M., & Gimeno, P. (2016). Experimental but not sex differences of a mental rotation training program on adolescents. *Frontiers in Psychology*, *7*, 1050. https://doi.org/10.3389/fpsyg.2016.01050

Sanmugam, M., Zaid, N. M., Mohamed, H., Abdullah, Z., Aris, B., & Suhadi, S. M. (2015). Gamification as an educational technology tool in engaging and motivating students; An analyses review. *Advanced Science Letters*, *21*(10), 3337–3341. https://doi.org/10.1166/asl.2015.6489

Shank, D. B., & Cotten, S. R. (2014). Does technology empower urban youth? the relationship of technology use to self-efficacy. *Computers and Education*, *70*, 184–193. https://doi.org/10.1016/j.compedu.2013.08.018

Singh, M., & Sun, D. (2025). Evaluating Minecraft as a game-based metaverse platform: Exploring gaming experience, social presence, and STEM outcomes. *Interactive Learning Environments*, 1–23. https://doi.org/10.1080/10494820.2025.2459200

Sırakaya, M., & Sırakaya, D. A. (2022). Augmented reality in STEM education: A systematic review. *Interactive Learning Environments*, *30*(8), 1556–1569. https://doi.org/10.1080/10494820.2020.1722713

Stohlmann, M. S. (2023). Categorization of game-based learning in middle school mathematics - A review. *Middle School Journal*, *54*(5), 16–26. https://doi.org/10.1080/00940771.2023.2254175

Su, J., & Yang, W. (2024). STEM in early childhood education: A bibliometric analysis. *Research in Science and Technological Education*, *42*(4), 1020–1041. https://doi.org/10.1080/02635143.2023.2201673

Sun, D., Zhan, Y., Wan, Z. H., Yang, Y., & Looi, C. K. (2023). Identifying the roles of technology: A systematic review of STEM education in primary and secondary schools from 2015 to 2023. *Research in Science and Technological Education*, *43*(1), 145–169. https://doi.org/10.1080/02635143.2023.2251902

Sun, L., Kangas, M., & Ruokamo, H. (2023). Game-based features in intelligent game-based learning environments: A systematic literature review. *Interactive Learning Environments*. https://doi.org/10.1080/10494820.2023.2179638

Takeuchi, M. A., Sengupta, P., Shanahan, M. C., Adams, J. D., & Hachem, M. (2020). Transdisciplinarity in STEM education: A critical review. *Studies in Science Education*, *56*(2), 213–253. https://doi.org/10.1080/03057267.2020.1755802

Tene, T., Vique López, D. F., Valverde Aguirre, P. E., Cabezas Oviedo, N. I., Vacacela Gomez, C., & Bellucci, S. (2025). A systematic review of serious games as tools for STEM education. *Frontiers in Education*, *10*, 1432982. https://doi.org/10.3389/feduc.2025.1432982

van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

Vedrenne-Gutiérrez, F., López-Suero, C. del C., De Hoyos-Bermea, A., Mora-Flores, L. P., Monroy-Fraustro, D., Orozco-Castillo, M. F., Martínez-Velasco, J. F., & Altamirano-Bustamante, M. M. (2024). The axiological foundations of innovation in STEM education – A systematic review and ethical meta-analysis. *Heliyon*, *10*(12). https://doi.org/10.1016/j.heliyon.2024.e32381

Videnovik, M., Vold, T., Kiønig, L., Madevska Bogdanova, A., & Trajkovik, V. (2023). Game-based learning in computer science education: A scoping literature review. *International Journal of STEM Education*, *10*(1). https://doi.org/10.1186/s40594-023-00447-2

Wen, Y. (2021). Augmented reality enhanced cognitive engagement: Designing classroom-based collaborative learning activities for young language learners. *Educational Technology Research and Development*, *69*(2), 843–860. https://doi.org/10.1007/s11423-020-09893-z

Winberg, C., Adendorff, H., Bozalek, V., Conana, H., Pallitt, N., Wolff, K., Olsson, T., & Roxå, T. (2019). Learning to teach STEM disciplines in higher education: A critical review of the literature. *Teaching in Higher Education*, *24*(8), 930–947. https://doi.org/10.1080/13562517.2018.1517735

Zhan, Z., Tong, Y., Lan, X., & Zhong, B. (2024). A systematic literature review of game-based learning in artificial intelligence education. *Interactive Learning Environments*, *32*(3), 1137–1158. https://doi.org/10.1080/10494820.2022.2115077

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Computational Thinking and STEM Education

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Chapter Highlights

This section summary provides the reader with a concise, yet comprehensive overview of the main concepts, frameworks, and findings discussed in the section on computational thinking and STEM education, highlighting its significance, key components, and implications for teaching, learning, and future research.

- 21st Century Skills – The importance of acquiring 21st century skills in today's world
- The Emergence and Importance of Computational Thinking – The importance and emergence of computational thinking in acquiring 21st century skills
- Definition and Components of Computational Thinking – Researchers' explanations of computational thinking and the skills of decomposition, abstraction, algorithmic thinking, debugging, generalization, and evaluation
- Computational Thinking and STEM Education – The connection between computational thinking and STEM education
- Discussion and Conclusion – The integration of computational thinking and STEM education into teaching programs

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Introduction

The concept of STEM, consisting of mathematics, engineering, science, and technology disciplines is said to have emerged within the last twenty years due to its focus on 21st-century skills (CS) and its incorporation of various disciplines (Langdon et al., 2011). Therefore, STEM education, which facilitates the use of technology and supports the development of 21st-CS through its interdisciplinary approach, is described as a teaching approach that combines engineering, mathematics, technology, and science to transform theory into practice (Meyrick, 2011).

One of the fundamental aims of STEM education is to prepare students with the 21st-CS required to contribute to the economy, foster competitiveness, and develop individuals who will benefit their countries (Morrison, 2006; Williams, 2011). Additionally, the aim is to facilitate learning through STEM education and provide a holistic approach through interdisciplinary connections (Smith & Karr-Kidwell, 2000). STEM education, which covers mathematics, engineering, technology and science, has attracted significant global interest thanks to its potential to develop real-world applications and enhance problem solving skills, as well as its interdisciplinary nature (Margot & Kettler, 2019). STEM education is crucial for achieving the United Nations' Sustainable Development Targets and improving educational standards (Jamali et al., 2022).

21st-Century Skills and Education

In the 21st century, referred to as the digital information age, the importance of developing high-level skills beyond academic knowledge is strongly emphasised (González-Pérez & Ramírez-Montoya, 2022). In this particular context, developing students' skills in algorithmic thinking, abstraction, problem solving, evaluation, and analysis during primary, secondary, and high school is crucial for the development of critical skills in university education (González-Pérez & Ramírez-Montoya, 2022). In the 21st-century, students are expected to be able to generate knowledge and apply it to new problem situations, rather than simply acquiring ready-made knowledge (Wagner, 2008). These characteristics expected of students in today's society are referred to as 21st-CS.

Today, 21st-CS are defined as problem solving, collaboration, critical thinking, communication, adaptability, technological literacy, financial literacy and global competencies (Partnership for 21st Century Skills [P21], 2009). Meanwhile, Lai and Viering (2012) outlined 21st-CS as comprising critical thinking, motivation, creativity, collaboration and metacognitive abilities. They presented the P21 framework alongside these skills, which are crucial for all 21st-century students, as shown in Figure 1 (P21, 2009).

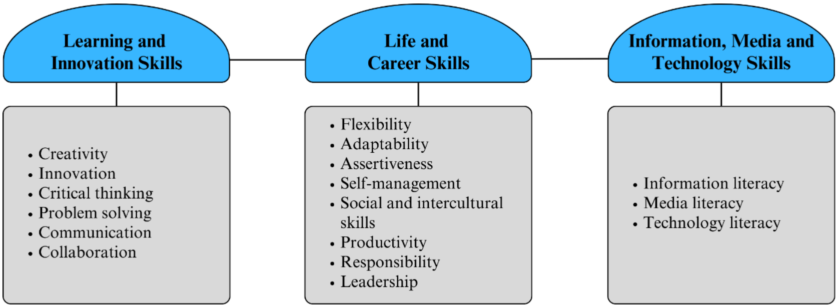

Figure 1. 21st-CS within the P21 Framework

STEM disciplines focus on developing students' communication, adaptability, problem solving, scientific thinking, self-regulation, innovation and creativity skills, thereby emphasising 21st-century learning outcomes (Bybee, 2010a). Students are expected to possess these skills and be able to apply their knowledge in different fields (Nargund-Joshi et al., 2013). Consequently, the structure of STEM education meets the objectives of contemporary teaching programmes (National Research Council [NRC], 2014). In line with this, engineering, innovation, problem solving and computational thinking (CT) are seen as being at the forefront of what is expected of students today (Bybee, 2010b).

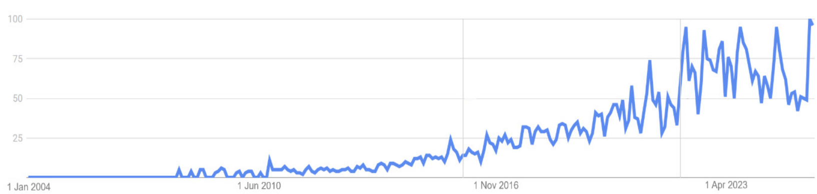

Figure 2. Google Trends search results for "CT" worldwide between 2004 and 2025

CT, which involves problems solving, designing systems and attempting to understand behaviour using fundamental computer science concepts, is one of the 21st-CS (Wing, 2006). The importance of CT is emphasised in the current climate, and research on this concept is increasing. Figure 2 shows a graph obtained by searching for the term "CT" on Google Trends. Examining the figure shows that studies related to CT have gained momentum since

2006, with an increasing research trend in recent years.

The Emergence and Importance of Computational Thinking

It can be stated that the primary researchers responsible for the emergence and significance of CT as a key concept are Seymour Papert and Jeannette Wing (Lodi & Martini, 2021). When CT is considered an ability that students should possess in addition to mathematics, writing, and reading (Wing, 2006), the idea of providing programming education to every student at the K-12 level dates back to Seymour Papert's work at the Massachusetts Institute of Technology in the 1980s.

Papert took the first steps towards what he termed procedural thinking with the aid of programming in his book Mindstorms: Children, 20 Computers, and Powerful Ideas (Papert, 1980). Therefore, it was expressed without a detailed definition by Seymour Papert (1980). Papert conducted research on how to use computer software to solve geometry problems. In this context, Papert (1980) stated that computers develop ways of accessing information and thinking, and contribute to the shaping of learning.

Papert was the first researcher to introduce the concept of CT. Meanwhile, Wing is widely recognised as the first researcher to define the concept using a pedagogical approach, drawing on principles from computer science (Lodi & Martini, 2021). In 2006, Wing provided a clearer definition of CT, stating that it is "the process of using concepts from computer science to understand human behavior, solve problems, and design systems". In this context, Wing (2006) emphasised that CT is a problem solving approach utilising computer science, and that it is a skill set not only for computer scientists, but for all individuals.

Wing (2006) described these skills as iterative thinking, problem solving, decomposition, abstraction, debugging and correction, and reasoning. When describing these characteristics, Wing stated that CT is 'a fundamental ability, not rote learning', 'a conceptualisation, not programming', 'an idea, not artificial', 'thinking like a human, not like a computer', and 'the ability to understand and solve scientific problems through mathematical thinking as an intellectual endeavour'.

CT involves abstraction, debugging and testing, as well as a problem solving approach based on interaction and collaboration with others (Brennan & Resnick, 2012). It is important for education systems to combine students' CT skills with technology to develop their problem solving and thinking abilities (Tsai et al., 2021). In today's technological age, the International Society for Technology in Education (ISTE) has outlined various standards that should be instilled in students based on the need for continuous self-improvement. These standards are provided in Table 1 (ISTE, 2016). Examination of the student standards established by ISTE reveals that students are described as digital citizens, competent learners, knowledge builders, computational thinkers, innovative designers, global collaborators, and creative communicators. Among these characteristics, CT occupies a particularly important position. Computational thinkers are defined as individuals who can use technology to understand and solve problems, develop solutions, and test them.

Table 1. ISTE Student Standards

ISTE STUDENT STANDARDS	
Competent Learner	Students are informed through education and utilize technology to achieve their goals.
Digital Citizen	Students recognize the rights, responsibilities, and opportunities of living, learning, and working in an interconnected digital world and act in safe, legal, and ethical ways.
Constructing knowledge	Students use and critically edit digital tools to construct knowledge, produce creative works, and create meaningful learning experiences for themselves and others.
Innovative design	Students identify problems with new, useful, or creative solutions using technology and create a solution design process.
Computational Thinker	Students use technological methods to understand and solve problems and to develop and test solutions.
Creative Communicator	Students communicate openly and express themselves creatively using platforms, tools, styles, formats, and digital media appropriate to their purposes.
Global Collaborator	Students work effectively in local and global teams, collaborating and broadening their perspectives using digital tools to enrich their learning.

Along with the standards expected to be instilled in students, ISTE (2018) has also defined certain standards for educators. These standards set by ISTE are presented in Table 2. When examining the educator standards, the characteristics of learner, leader, digital citizen, collaborator, designer, facilitator, and analyst come to the fore. It can be stated that educators possessing these characteristics will enable students to develop themselves in terms of the 21st-CS and CT skills they need to acquire.

Table 2. ISTE Educational Standards

ISTE EDUCATIONAL STANDARDS	
Learner	Educators are constantly learning, exploring and implementing proven, effective methods using technology to improve student learning.
Digital Citizen	Educators guide students to develop digital literacy, contribute positively to the digital world, and engage in legal and ethical practices.
Leader	To enhance student competencies, educators must provide technology-enhanced learning. They provide equal opportunities for all students to access digital tools and educational technologies. They demonstrate leadership in the adoption and improvement of new digital educational tools.
Designer	Educators use innovative digital tools and design unique, student-centered activities and environments for active and deep learning.
Collaborator	Educators collaborate with colleagues, parents, and students to develop unique applications using technology, discover and share resources, and solve technology problems.
Facilitator	Educators facilitate learning with technology to support students' competencies according to the ISTE Student Standards, creating opportunities that foster computational thinking in problem solving.
Analyst	By using technology, educators provide students with alternative ways to think about their learning and understand and use data to support them in achieving their learning goals.

When considering the student and educator standards established by ISTE, it is evident that CT processes come to the fore. The characteristics that CT processes should possess can be expressed as follows (Allsop, 2019):

- It is a cognitive process.
- It involves practices that trigger metacognitive thinking.
- It involves the application of knowledge processing thinking skills concepts and abilities.
- Students are expected to apply the concepts they have learned.
- It enables students who are sensitive to problems to develop effective solutions.

What is Computational Thinking?

The definition of CT is debated by many researchers. While some researchers argue that there is no need for a precise definition (Hu, 2011), studies in the field of education indicate that a definition is necessary (Barr & Stephenson, 2011; Hemmendinger, 2010; ISTE, 2011). In this context, Some CT definitions are given in Table 3.

Table 3. Definitions of CT

DEFINITIONS OF COMPUTATIONAL THINKING	
Wing (2006)	It is the process of solving problems, designing systems, and understanding human behavior using fundamental computer science concepts.
Denning (2009)	It is a process that involves thinking at different levels of abstraction, using mathematics to develop algorithms, and examining how well a solution scales across problems of different sizes.
Lu and Fletcher (2009)	It is a conceptual pathway necessary for the systematic, accurate, and efficient processing of information and tasks.
Hemmendinger (2010)	It is to teach them to think like economists, physicists, or artists and to understand how computing can be used to solve problems, create, and discover new questions that can be productively investigated.
Computing Research Association (2010)	It is a rich and evolving set of cognitive skills that are difficult to define precisely.
Wing (2011)	It is a process that requires formulating problems and expressing their solutions by transforming them into information that an information processing tool can effectively apply.
Aho (2012)	It is the implementation of the problem-solving process using computational steps and algorithms.
Furber (2012)	It is the process of recognizing computational aspects of the world around us, using tools and techniques to understand computer science, and being able to reason about both natural and artificial systems and processes.
Kafai and Burke (2013)	Drawing on the fundamental concepts, practices, and perspectives of computer science, computational participation can be expressed as the ability to solve problems with others, design systems with others for others, and understand the cultural and social nature of human behavior.
Yadav et al. (2017)	It is the mental process of abstracting problems and creating automatable solutions.
Manila et al. (2014)	It is the process of formulating and solving problems with the help of a set of computer science concepts and processes.

ISTE (2018) and the Computer Science Teacher Association [CSTA] (2017) have defined CT by highlighting the characteristics in their definitions. In making these definitions, they have also emphasised the five tendencies found in the characteristics of CT (CSTA, 2017; ISTE, 2021). These are:

- Confidence (ability to cope with problems)
- Persistence (ability to solve complex problems)
- Tolerance (ability to cope with uncertainty)
- Ability to cope with open ended problems
- Work ability with a team and communicate in order to achieve a

specific goal

Fundamental Skills in Computational Thinking

Researchers emphasise various skills when considering the characteristics of CT. Figure 3 shows these skills.

Figure 3. Fundemental Skills of CT

These skills are generally accepted to comprise the following components: pattern recognition, decomposition, algorithm creation, abstraction, generalisation and debugging.

Decomposition

Breaking down complex problems into simpler parts for detailed examination and analysis (Wing, 2006). This process can be described as dividing a problem situation into simpler parts (Conery et al., 2011), or building down a problem situation into simpler parts with the intention of reassembling them (Maharani et al., 2019). Csizmadia et al. (2015) describe decomposition as the process of building down a whole into its parts according to specific characteristics, and reflecting on those parts. When dividing a problem into sections, it is important to ensure that the sections can be solved independently and that the solutions can be combined to solve the entire problem (Liskov & Guttag, 2000). Examples of the decomposition step include preparing a simple electrical circuit (Gülbahar et al., 2020) and classifying a species (Barr & Stephenson, 2011).

Pattern Recognition

It is the dimension in which similar or different situations are investigated in the event of a problem (Csizmadia et al., 2015). The identification, classification and analysis of objects according to their characteristics can be described as stages in the pattern discovery process (Liu et al., 2006). In other words, it is the process of dividing problem situations into sub problems and then creating solutions based on the differences and similarities between these sections (British Broadcasting Corporation [BBC], 2019).

Abstraction

Abstraction is described as the foundation of CT and stands out as its distinguishing feature from other forms of thinking (Grover & Pea, 2013). It forms the basis of CT (Wing, 2008). Therefore, it is a dimension in which the problem is simplified by disregarding some of its details (Csizmadia et al., 2015). In this context, Csizmadia and colleagues (2015) explained abstraction ability as the process of making a situation more understandable by reducing unnecessary details.

Abstraction is the ability to decide which details are important and which details will not be included in the process when solving a problem situation (Selby, 2015). Therefore, abstraction becomes critical in determining which details are important when the problem situation becomes more complex (Aho, 2012). Similarly, Wing (2008) also explains abstraction as the decision-making process regarding which details we should emphasise and which details we can ignore throughout the process.

Modelling can be described as an important aspect of abstract thinking. The process of defining variables and modelling equations or inequalities for these variables is an important stage in problem solving and can be considered an abstraction skill (Barr & Stephenson, 2011). Abstraction and decomposition are interrelated processes (Liskov & Guttag, 2000).

Algorithm Creation

Throughout the process, algorithms play a significant role in computer science as they are coherent wholes that produce results, with their operations being clearly, explicitly and effectively sequenced (Schneider et al., 2015). As a method created to solve a problem (Sedgewick & Wayne, 2011), an algorithm refers to a set of logical, sequential operations performed to solve specific problems (Selby & Woollard, 2013). It can also be described as an abstraction of a system involving inputs, a series of steps and goal-oriented outcomes (Wing, 2014).

Once an algorithm has been developed, it can be used to solve similar problems; there is no need to create a new algorithm each time (Csizmadia et al., 2015). For instance, algorithms employed for fundamental mathematical operations can be applied to other problem solving scenarios (Csizmadia et al., 2015). In today's technological age, it has become increasingly important to develop algorithmic thinking among middle school students. This is because, among CT skills, algorithmic thinking enables students to identify appropriate steps for problem situations, find solutions and design solution plans (Neira et al., 2021).

Generalisation

Generalisation is a skill that enables problems to be solved quickly by drawing on previous solutions and constructing solution patterns based on students' prior experiences (Csizmadia et al., 2015). It can be described as a way of finding solutions to new problem situations based on problem situations that have been solved in the past (Csizmadia et al., 2015). Therefore, the skill of generalisation is a strategic skill with applicability, and mastering it is more challenging than mastering other skills (Selby, 2014).

Debugging

Determining whether there are errors in the solutions identified for resolving the problem situation can be described as testing, while identifying and correcting the identified errors can be described as debugging (Maharani et al., 2019). The debugging process constitutes an important dimension of the programming process because it requires a higher level of thinking skill than code writing ability (Liu et al., 2006). In this context, it is crucial to review the process of creating models for solving problem situations, identify errors and correct them when the solutions do not turn out as expected (Angeli et al., 2016). Therefore, CT skills such as debugging are effective in questioning the learning and teaching process and making inferences about problem situations (Gonzales, 2013).

Evaluation

It can be described as the process of determining which of the proposed solutions to problem situations is the best and explaining why the others are not as effective. It also aims to highlight the limitations of the solutions identified (Selby, 2014). Although debugging and evaluation dimensions are expressed as the final dimension among the components, they are dimensions that must be considered in relation to the steps taken at every stage of CT. That is, in problem solving situations, evaluations should be made at every stage and any errors should be debugged (Liu et al., 2006).

Techniques Used in the Application of Computational Thinking

Various techniques can be applied to teach CT skills in the curriculum. By applying these techniques, CT can be transformed into a teaching method separate from computer science. Csizmadia and colleagues (2015) describe these techniques as reflecting, coding, designing, analyzing, and applying (Figure 4).

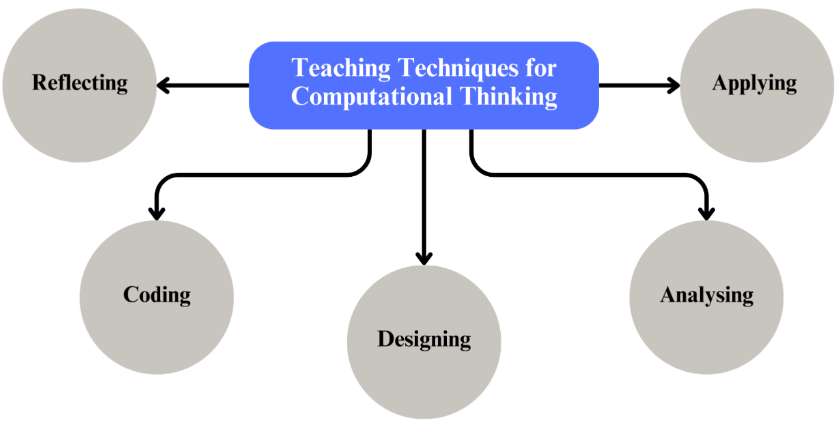

Figure 4. Techniques for Teaching CT

Reflecting

It can be described as the ability to draw honest and fair conclusions in complex problem situations. It establishes general rules and evaluations for determining the most appropriate intuitive methods and criteria for identifying the problem situation within the scope of CT (Csizmadia et al., 2015).

Coding

Coding is a fundamental computer science skill used to evaluate solutions by adapting them to the current problem and achieving a result under the necessary conditions. This allows for a systematic approach involving debugging, predicting outcomes and making logical inferences (Csizmadia et al., 2015).

Designing

Designs created for problem situations aim to determine effective solutions to reach a resolution. These solutions require CT abilities, such as algorithm design, decomposition, and abstraction (Csizmadia et al., 2015).

Analysing

The aim is to find a solution to the problem by breaking it down into subcomponents, eliminating unnecessary details and identifying common and distinct points based on the relationships between components. This process involves making assessments and logical inferences to improve understanding of the situation (Csizmadia et al., 2015).

Applying

It refers to the use of inferences obtained from other problem solving situations to solve a problem. In this way, the characteristics of previously established connections, similarities and differences are utilised. This enables different inferences to be made (Csizmadia et al., 2015).

Computational Thinking and STEM

Although CT originated in computer science, It's a way of looking at things, that has spread to other fields, with specific components and dimensions (Wing, 2008). CT therefore plays a key role in developing skills such as problem solving, collaboration, communication, critical thinking, global competence, technological literacy and financial literacy (Nouri et al., 2020). Developing these skills is said to contribute to individuals becoming competent, confident and determined problem solvers across many disciplines, including mathematics, science and the humanities (Román-González et al., 2018).

CT, recognised as interdisciplinary analytical thinking, is explained as follows: the way of solving a problem is explained by mathematical thinking; the way of designing and evaluating a large and complex system is explained by engineering thinking; and the way of understanding computability, intelligence, and human behaviour is explained by scientific thinking (Wing, 2008). CT enables the modelling of complex structures as well as the analysis of large data sets (Wing, 2008). Based on this, it can be stated that it is a skill that everyone working in many disciplines, such as mathematicians, computer scientists, and engineers, should possess (Wing, 2006).

As emphasised by Wing (2006), CT skills—including abstraction, decomposition, modelling, error correction, logical reasoning, and mathematical and engineering-based thinking—suggest that STEM studies, encompassing science, engineering, mathematics, and technology disciplines, are highly interrelated. The NRC (2010) report lists CT as one of the cognitive characteristics that an individual should possess in modern society, and the 2011 report emphasises that CT is present in all STEM fields and that individuals need to recognise and learn its applications in different fields in order to develop their expertise in this area (NRC, 2011). Furthermore, research has demonstrated the universal applicability of CT across all disciplines (Barr & Stephenson, 2011; Conery et al., 2011; Wing, 2006).

In light of these developments and today's advanced technological structures, it is inevitable that CT concepts and practices will be incorporated into STEM education. Therefore, integrating STEM and CT can greatly enhance people's ability to cope with complex problems (Swaid, 2015). Various studies have examined STEM and CT skills (Jiang et al., 2022; Pewkam & Chamrat, 2022; Shang et al., 2023; Srisangngam & Dechsura, 2020; Qian, 2019). These studies also emphasise that STEM and CT impart skills that facilitate daily life.

According to Thomasian (2011), STEM education has two main purposes.

1. to encourage students graduating from university to pursue careers in STEM fields;
2. to develop the abilities of all students to create creative solutions in daily life using concepts from STEM fields.

STEM education is recognised as an effective way of developing students' problem solving abilities and overcoming the challenge of integrating subjects into the curriculum, while also creating opportunities (Margot & Kettler, 2019). Additionally, STEM education is recognised as an effective means of developing higher-order thinking skills, establishing a professional identity and increasing motivation, while also improving academic achievement

(Li, 2020).

In the 21st century, CT skills have emerged as critical in the development of STEM fields (Law et al., 2021). CT is not merely about processing information; it is a way of thinking that is important in teaching STEM disciplines (Li et al., 2020). Therefore, integrating CT into STEM education has become important for developing students' analytical skills in the problem solving process (Mintii, 2023). It is emphasised that this integration process is also important in educational processes such as STEAM, where STEM education is combined with art (Bell & Bell, 2018).

Discussion

STEM education establishes strong links with 21st-CS and real-life situations (English, 2016). In this context, attention is drawn to 21st-CS in STEM education, and it is argued that 21st-CS should be imparted in all subjects and that STEM education can establish connections across all disciplines (English, 2016). To achieve this, it is necessary to cultivate individuals with 21st-CS such as problem solving, collaboration, creativity and communication, and education systems must be transformed accordingly (Faber et al., 2013; NRC, 2012). STEM education also plays an important role in supporting students' creativity, developing their problem solving abilities, and nurturing productive individuals (Daugherty, 2009).

According to ISTE (2023), CT is a type of literacy that involves problem decomposition, abstraction, pattern recognition and algorithmic properties, and is intended to develop individuals who can find solutions to contemporary problems. Furthermore, it presents the process as a systematic sequence of steps. However, CT is not about thinking like a computer; rather, it focuses on developing all the mental tools necessary for the effective use of computing in solving problems (Lu & Fletcher, 2009). Similarly, CT goes beyond human interaction with and use of computers and technology, encouraging the creation of new explanations, designs for tools, and creativity (Mishra & Yadav, 2013).

Conclusion

Technological developments and modern living conditions are guiding students towards developing themselves in multiple ways. To achieve this, critical skills have come to the forefront. When these abilities are referred to as 21st-CS, CT is actively emphasized by researchers (Aho, 2012; Allsop, 2019; Hu, 2011; Wing, 2006; Wing, 2014).

Wing (2011) defines CT as a thinking process That involves formulating problems and solutions in a way that can be effectively implemented by a computational unit, which is the key to success in this field. The skills expected to be acquired by students have been expressed in various ways based on the definition of CT (Angeli et al., 2016; Barr & Stephenson, 2011; Wing, 2006; Wing, 2011). The following skills come to the fore: differentiation, abstraction, algorithmic thinking, pattern formation, debugging, generalisation and evaluation.

Activities that bring together different disciplines and implement applications are becoming increasingly important in CT development. This situation highlights the importance of STEM education. STEM is an interdisciplinary, student-centred approach to education that uses scientific research methods to solve problems related to daily life (Bender, 2015).

STEM education and interdisciplinary activities are critical for increasing students' interest in various scientific fields and incorporating such education into the curriculum (Knezek et al., 2013). In this context, CT also plays a crucial role in enabling students to establish effective connections. Consequently, it is crucial that teaching programs include content that enables students to develop skills such as algorithmic thinking, decomposition, understanding abstraction, and generalization.

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REFERENCES

Aho, A. V. (2012). Computation and computational thinking. *The Computer Journal*, *55*(7), 832-835. https://doi.org/10.1093/comjnl/bxs074

Allsop, Y. (2019). Assessing computational thinking process using a multiple evaluation approach. *International journal of child-computer interaction, 19*, 30-55. https://doi.org/10.1016/j.ijcci.2018.10.004

Angeli, C., Voogt, J., Fluck, A., Webb, M., Cox, M., Malyn-Smith, J., & Zagami, J. (2016). A K-6 computational thinking curriculum framework: Implications for teacher knowledge. *Journal of Educational Technology & Society,* 19(3), 47-57.

Barr, V., & Stephenson, C. (2011). Bringing computational thinking to K-12: what is Involved and what is the role of the computer science education community? *Acm Inroads*, 2(1), 48-54. https://doi.org/10.1145/1929887.1929905

Bell, J., & Bell, T. (2018). Integrating computational thinking with a music education context. Informatics in Education, 17(2), 151-166. https://doi.org/10.15388/infedu.2018.09

Bender, W. N. (2015). *Differentiating instruction for students*, (Ed.) Thousand Oaks, CA: Corwin Press.

Brennan, K., & Resnick, M. (2012). New frameworks for studying and assessing the development of computational thinking. *In Proceedings of the 2012 annual meeting of the American educational research association, Vancouver, Canada.*

British Broadcasting Corporation [BBC]. (2019). Pattern recognition.

Bybee, R. W. (2010a). What is STEM education? Science, 329(5995), 996-996. https://doi.org/10.1126/science.1194998

Bybee, R. W. (2010b). Advancing STEM education: A 2020 vision. *Technology and Engineering Teacher*, *70*(1), 30.

Computer Science Teacher Association [CSTA] (2017). K-12 Computer Science Standards. Association for Computing Machinery, New York, NY, United States.

Conery, L., Stephenson, C., Barr, D., Barr, V., Harrison, J., James, J., & Sykora, C. (2011). Computational thinking: Leadership toolkit (1st ed.). International Society for Technology in Education.

Csizmadia, A., Curzon, P., Dorling, M., Humphreys, S., Ng, T., Selby, C., and Woollard, J. (2015). Computational thinking-A guide for teachers. Swindon, Computing at School.

Daugherty, M. K. (2013). The prospect of an "A" in STEM education. *Journal of STEM Education: Innovations and Research*, *14*(2), 10-15.

Denning, P. J. (2009). The profession of IT Beyond computational thinking. *Communications of the ACM*, 52(6), 28-30. https://doi.org/10.1145/1516046.1516054

English, L. D. (2016). Advancing mathematics education research within a STEM environment. In K. Makar, S. Dole, J. Visnovska, M. Goos, A. Bennison, & K. Fry (Eds.), Research in mathematics education in Australasia 2012–2015 (pp. 353–371). Singapore: Springer. https://doi.org/10.1007/978-981-10-1419-2_17

Faber, M., Unfried, A., Wiebe, E.N., Corn, J. Townsend, L.W., & Collins, T.L. (2013). Student attitudes toward stem: the development of upper elementary school and middle/high school student surveys. In Paper presented at the 120th ASEE Annual Conference ve Exposition, Atlanta, GA: US.

Furber, S. (2012). *Shut down or restart? The way forward for computing in UK schools.* Technical report, The Royal Society, London.

Gonzalez, J. J. (2013). My Journey With Inquiry-Based Learning. *Journal on Excellence in College Teaching*, *24*(2), 33-50.

González-Pérez, L. I., & Ramírez-Montoya, M.S. (2022). Components of Education 4.0 in 21st Century Skills Frameworks: Systematic Review. Sustainability, 14, 1493. https://doi.org/10.3390/su14031493

Grover, S., & Pea, R. (2013). Computational thinking in K–12 A review of the state of the field. Educational Researcher, 42(1), 38-43. https://doi.org/10.3102/0013189X12463051

Hemmendinger, D. (2010). A plea for modesty. *Acm Inroads*, 1(2), 4-7. https://doi.org/10.1145/1805724.1805725

Hu, C. (2011). Computational thinking: what it might mean and what we might do about it. *Proceedings of the 16th annual joint conference on Innovation and Technology in Computer Science Education*. Darmstadt, Germany. https://doi.org/10.1145/1999747.1999811

International Society for Technology in Education [ISTE], (2011). *Operational Definition for Computational Thinking.* https://c.ymcdn.com/sites/www.csteachers.org/resource/resmgr/CompThinkingFlyer.pdf

International Society for Technology in Education [ISTE], (2016). ISTE Standards For Students. https://www.iste.org/standards/for-students

International Society for Technology in Education [ISTE], (2018). ISTE Standarts for Educators. https://www.iste.org/standards/computational-thinking

International Society for Technology in Education [ISTE], (2023). Computational Thinking. https://www.iste.org/areas-of-focus/computationalthinking-in-the-classroom

Jamali, S. M., Ebrahim, N. A., & Jamali, F. (2022). The role of STEM education in improving the quality of education: A bibliometric study. *International Journal of Technology and Design Education*, *33*(3), 819-840. https://doi.org/10.1007/s10798-022-09762-1

Jiang, H., Atuquil Islam, A. Y. M., Gu, X., & Guan, J. (2022). How do thinking styles and STEM attitudes have effects on computational thinking? A structural equation modeling analysis. *J Res Sci Teach. 2023,* 1-29.

Kafai, Y. B., & Burke, Q. (2013). The social turn in K-12 programming: moving from computational thinking to computational participation. [Conference session]. *In Proceeding of the 44th ACM technical symposium on computer science education* (pp. 603-608). https://doi.org/10.1145/2445196.2445373

Knezek, G., Christensen, R., Tyler-Wood, T., & Periathiruvadi, S. (2013). Impact of environmental power monitoring activities on middle school student perceptions of STEM. *Science Education International, 24*(1), 98-123.

Lai, E. R., & Viering, M. (2012). Assessing 21st century skills: Integrating research findings. *Vancouver, B.C.: Pearson.*

Langdon, D., McKittrick, G., Beede, D., Khan, B., & Dom, M. (2011). STEM: Good jobs now and for future. *U.S. Department of Commerce Economics and Statistics Administration*, *3*(11), 2.

Law, K. E., Mageswary, K., & Rozniza, Z. (2021). Computational thinking in STEM education among matriculation science students. Asia Pacific Journal of Educators and Education, 36(1), 177-194. https://doi.org/10.21315/apjee2021.36.1.10

Li, Y. (2020). Six years of development in promoting identity formation of STEM education as a distinct field. International Journal of STEM Education, 7(1), 59. https://doi.org/10.1186/s40594-020-00257-w

Li, Y., Schoenfeld, A. H., diSessa, A. A., Graesser, A. C., Benson, L. C., English, L. D., & Duschl, R. A. (2020). On computational thinking and STEM education. *Journal for STEM Education Research*, *3*(2), 147-166. https://doi.org/10.1007/s41979-020-00044-w

Liskov, B., & Guttag, J. (2000). Program development in JAVA: Abstraction, Specification and Onject Orient Design. Boston: Adison Wesley.

Liu, J., Sun, J., & Wang, S. (2006). Pattern recognition: An overview. IJCSNS International Journal of Computer Science and Network Security, 6(6), 57-61.

Lodi, M., & Martini, S. (2021). Computational thinking, between Papert and Wing. Science & Education, 30(4), 883-908. https://doi.org/10.1007/s11191-021-00202-5

Lu, J. J., & Fletcher, G. H. (2009). Thinking about computational thinking. ACM SIGCSE Bulletin, 41(1), 260-264. https://doi.org/10.1145/1539024.1508959

Maharani, S., Kholid, M. N., Pradana, L. N., & Nusantara, T. (2019). Problem solving in the context of computational thinking. Infinity Journal, 8(2), 109-116. https://doi.org/10.22460/infinity.v8i2.p109-116

Mannila, L., Dagiene, V., Demo, B., Grgurina, N., Mirolo, C., Rolandsson, & L., Settle, A. (2014). Computational thinking in K-9 education. In: *Proceedings of the Working Group Reports of the 2014 on Innovation & Technology in Computer Science Education Conference,* ITiCSE-WGR, 1–29. ACM, New York https://doi.org/10.1145/2713609.2713610

Margot, K. C., & Kettler, T. (2019). Teachers' perception of STEM integration and education: a systematic literature review. *International Journal of STEM Education*, *6*(1), 1-16. https://doi.org/10.1186/s40594-018-0151-2

Meyrick, K. M. (2011). How STEM education improves student learning. *Meridian K-12 School Computer Technologies Journal*, *14*(1), 1–5.

Mintii, M. M. (2023). STEM Education and Personnel Training: Systematic Review. Journal of Physics Conference Series, 2611(1), 012025. https://doi.org/10.1088/1742-6596/2611/1/012025

Mishra, P., & Henriksen, D. (2013). A new approach to defining and measuring creativity: Rethinking technology & creativity in the 21st century. *TechTrends*, 57(5), 10. https://doi.org/10.1007/s11528-013-0685-6

Morrison, J. (2006). Attributes of STEM education: The student, the school, the classroom. *TIES (Teaching Institute for Excellence in STEM)*, *20*, 2-7.

Nargund-Joshi, V., Liu, X., Chowdhary, B., Grant, B., & Smith, E. (2013). Understanding meanings of interdisciplinary science inquiry in an era of next generation science standards. In *annual meeting of National Association for Research in Science Teaching, Rio Grande, Puerto Rico*.

National Research Council [NRC], (2010). *Report of a workshop on the scope and nature of computational thinking*. The National Academies Press, Washington, DC.

National Research Council [NRC], (2011). *Report of a Workshop of Pedagogical Aspects of Computational Thinking.* The National Academies Press, Washington, DC.

National Research Council [NRC], (2012). A Framework for K12 Science Education: Practices, Cross Cutting Concepts, and Core Ideas. The National Academies Press, Washington, DC.

National Research Council [NRC], (2014). STEM learning is everywhere: summary of a convocation on building learning systems. *The National Academies Press*, Washington, DC.

Neira, R. H., Garcia-Iruela, M. & Connolly, C. (2021). Developing and accessing computational thinking in secondary education using a TPACK guided scratch visual execution environment. International Journal of Computer Science Education in Schools, 4(4), 3-23. https://doi.org/10.21585/ijcses.v4i4.98

Nouri, J., Zhang, L., Mannila, L., & Norén, E. (2020). Development of computational thinking, digital competence and 21st century skills when learning programming in K-9. *Education Inquiry*, 11(1), 1-17. https://doi.org/10.1080/20004508.2019.1627844

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. New York: Basic Books. Inc.

Partnership for 21st Century Skills [P21], (2009). P21 framework definitions.

Pewkam, W., & Chamrat, S. (2022). Pre-service teacher training program of stem-based activities in computing science to develop computational thinking. *Informatics in education. 21*(2), 311–329. https://doi.org/10.15388/infedu.2022.09

Qian, Y. (2019). Effectiveness of explicıt guidance and practıces on abstractıon (EGPA): focus on computatıonal tasks ın a stem-ıntegratıve robotıc educatıon program for fıfth grade students. [Doctoral dissertation, University of Georgia]. UCL Discovery.

Román-González, M., Pérez-González, J. C., Moreno-León, J., & Robles, G. (2018). Extending the nomological network of computational thinking with non-cognitive factors. *Computers in Human Behavior*, 80, 441-459. https://doi.org/10.1016/j.chb.2017.09.030

Schneider, G, Gersting, J., & Brinkman, B. (2015). *Invitation to computer science*. Gale, Cengage Learning.

Sedgewick, R., & Wayne, K. (2011). *Algorithms*. Addison-wesley professional.

Selby, C. C. (2014). *How can the teaching of programming be used to enhance computational thinking skills?* (Doctoral dissertation, University of Southampton).

Selby, C. C. (2015). Relationships: computational thinking, pedagogy of programming, and Bloom's Taxonomy. In Proceedings of the Workshop in Primary and Secondary Computing Education (pp. 80-87). ACM. https://doi.org/10.1145/2818314.2818315

Selby, C., & Woollard, J. (2013). Computational thinking: the developing definition, University of Southampton.

Shang, X., Jiang, Z., Chlang, F. K., Zhang, Y., & Zhu, D. (2023). Effects of robotics STEM camps on rural elementary students' selfefficacy and computational thinking. *Education Tech Research Dev. 71,* 1135–1160. https://doi.org/10.1007/s11423-023-10191-7

Smith, J., & Karr-Kidwell, P. J. (2000). The Interdisciplinary Curriculum: A Literary Review and a Manual for Administrators and Teachers.

Srisangngam, P., & Dechsura, C. (2020). STEM education activities development to promote computational thinking's students. 2020 International STEM Education Conference (iSTEM-Ed 2020). Huahin, Thailand. https://doi.org/10.1109/iSTEM-Ed50324.2020.9332734

Swaid, S. I. (2015). Bringing computational thinking to STEM education. *Procedia Manufacturing*, 3, 3657-3662. https://doi.org/10.1016/j.promfg.2015.07.761

Thomasian, J. (2011). Building a science, technology, engineering, and math education agenda: an update of state actions. *NGA Center for Best Practices*. *Washington.*

Tsai, L. T., Chang, C.C., & Cheng, H. T. (2021). Effect of a STEM-oriented course on students' marine science motivation, interest, and achievements. *Journal of Baltic Science Education, 20(1),* 134-145. https://doi.org/10.33225/jbse/21.20.134

Wagner, T. (2008). Rigor redefined. *Educational Leadership*, *66*(2), 20-24.

Williams, J. (2011). STEM education: Proceed with caution. *Design and Technology Education: An International Journal*, *16*(1), 26-35.

Wing, J. (2014). Computational thinking benefits society. *Journal of Computing Sciences in Colleges*, *24*(6), 6–7.

Wing, J. M. (2006). Computational thinking. *Communications of the ACM*, *49*(3), 33-35. https://doi.org/10.1145/1118178.1118215

Wing, J. M. (2008). Computational thinking and thinking about computing. Philosophical Transactions of the Royal Society A – Mathematical Physical and Engineering Sciences, 366(1881), 3717–3725. https://doi.org/10.1098/rsta.2008.0118

Wing, J. M. (2011). Research Notebook: Computational thinking -what and why? *The Link Magazine,* Carnegie Mellon University, Pittsburgh.

Yadav, A., Good, J., Voogt, J., & Fisser, P. (2017). Computational thinking as an emerging competence domain. *Competence-based vocational and professional education: Bridging the worlds of work and education*, 1051-1067. https://doi.org/10.1007/978-3-319-41713-4_49

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Chapter 6

STEM, Metaverse and Augmented Reality

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Chapter Highlights

The following points outline the core dimensions, opportunities, and challenges of integrating immersive technologies into STEM education, with a particular emphasis on pedagogical innovation, learning outcomes, assessment and learning analytics, and future-oriented instructional models. Together, they highlight the transformative potential of immersive technologies while underscoring the need for thoughtful, ethical, and sustainable implementation in STEM teaching and learning.

- Key Components of STEM Education – Integration of science, technology, engineering, and mathematics in teaching and learning.
- Role of Immersive Technologies – Impact of Augmented Reality, Virtual Reality, Metaverse applications on STEM education.
- Pedagogical Impacts and Learning Outcomes – Student interaction, collaboration, active learning, and development of scientific process skills.
- Assessment and Learning Analytics – Personalized feedback, learning analytics, and innovative assessment methods.
- Challenges and Limitations – Technical infrastructure, costs, privacy, and teacher training obstacles.
- Future Directions – Adaptive learning models, AI integration, inclusive policies, and interdisciplinary applications.

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Introduction

STEM (Science, Technology, Engineering, and Mathematics) education embodies a cohesive, interdisciplinary methodology aimed at providing students with the requisite knowledge and skills to tackle intricate global issues of the 21st century, including climate change and resource depletion (Marzuki et al., 2024). STEM education combines science, technology, engineering, and math to help students see the whole picture and become creative, imaginative problem-solvers.

The complexity of contemporary global issues requires students to move beyond rote memorization and disciplinary silos, embracing an educational paradigm that promotes critical, logical, and systematic thinking (Kelley & Knowles, 2016; Smith et al., 2022). This interdisciplinary approach helps students connect STEM subjects in relevant ways, which improves their problem-solving skills and knowledge of concepts (Thibaut et al., 2018).

Recent advances in educational technologies have strengthened STEM education by providing interactive, immersive, and student-centered learning experiences (Petrov & Atanasova, 2020). Among these, Metaverse and Augmented Reality (AR) technologies have garnered attention for their potential to transform traditional classrooms into highly engaging environments. Augmented Reality overlays digital content onto real-world contexts to support conceptual visualization, while the Metaverse provides collaborative virtual spaces where students can interact, problem-solve, and engage authentically beyond physical limitations (Tene et al., 2024).

These immersive technologies foster active learning, collaboration, and critical thinking, improving student engagement, knowledge retention, and performance across STEM disciplines (AlGerafi et al., 2023). In engineering education, AR enhances visualization and problem-solving skills critical for addressing societal challenges (Suhail et al., 2024). Also, AR and Metaverse apps help people learn 21st-century skills like creativity, innovation, communication, digital literacy, and teamwork. They also help people understand complex ideas better by giving them more opportunities to work together (Akçayır & Akçayır, 2017).

This chapter examines the intersection of STEM, Metaverse, AR, with an emphasis on theoretical foundations, practical applications, pedagogical impacts, and emerging challenges. By systematically reviewing current research, it highlights effective educational practices and provides insights into future directions for integrating immersive technologies into STEM curricula.

Emerging Technologies in STEM Education: A Theoretical Framework

STEM education is inherently interdisciplinary, combining scientific inquiry, technological innovation, engineering design, and mathematical reasoning into holistic learning experiences. This interdisciplinary nature aligns closely with the demands of the 21st century, where problem-solving often requires knowledge and skills across multiple domains (Marzuki et al., 2024). The incorporation of emerging technologies into STEM significantly enhances this potential by offering novel opportunities for visualization, simulation, and experimentation. These technologies allow students to participate in genuine, real-world problem-solving situations that require the simultaneous application of knowledge from various disciplines (Smith et al., 2022). Technologies such as VR, AI, AR exemplify this by facilitating experiential learning and fostering interdisciplinary approaches to complex problems (Chiu & Li, 2023). Moreover, integrating STEM content through inquiry-based and design-based learning enhances students' skills across diverse STEM disciplines and promotes a profoundly interdisciplinary learning environment. Despite this potential, a lack of synthesized frameworks has hindered the establishment of a robust theoretical foundation for STEM education (Aguilera et al., 2021).

The TPACK framework, which is based on Shulman's Pedagogical Content Knowledge, is a solid theoretical tool for looking at the complicated relationship between technology, pedagogy, and content that is needed for good teaching (Li & Li, 2024). This framework emphasizes that successful technology integration arises from the synergistic interplay of technological knowledge, pedagogical strategies, and subject-specific content, moving beyond simplistic views of technology as merely an additive tool (Jimoyiannis, 2010). Early research primarily established TPACK's theoretical underpinnings, while recent studies have solidified its utility in STEM education, particularly in supporting teacher adaptability, blended learning, and professional development (Irwanto, 2021). Within STEM contexts, TPACK highlights the necessity for educators to master content and pedagogy while also developing competencies in using advanced technologies such as AR and Metaverse platforms.

From a digital transformation perspective, STEM education is increasingly shaped by global policy frameworks, such as OECD's Learning Compass 2030 and UNESCO's guidelines on digital literacy. These frameworks emphasize not only the integration of emerging technologies but also the cultivation of adaptable, future-ready learners, thereby influencing curriculum development and pedagogical practices in higher education (Lyngdorf et al., 2024). They support transformative learning opportunities that cultivate 21st-century skills such as creativity, critical thinking, collaboration, and problem-solving, which are crucial for tackling global societal issues like climate change and significant human migrations (Rusmin et al., 2024). Furthermore, these directives promote the incorporation of value-based competencies alongside academic and technical skills, fostering sustainability, ethical awareness, and digital literacy (Cañavate et al., 2025).

This paradigm shift leverages technologies such as AR, VR, and Mixed Reality to create dynamic, interactive learning experiences within STEM disciplines. AR, for instance, overlays digital content onto real-world contexts to enhance conceptual visualization, while the Metaverse offers immersive, multi-user environments where students can collaborate, engage in problem-solving, and experience authentic scenarios (Tene et al., 2024). Combining these technologies helps people understand difficult ideas better, makes them more motivated, makes group learning more fun, and helps them learn how to be ethical and value-based. Empirical research illustrate their teaching efficacy, including enhancements in student engagement, knowledge retention, and performance across STEM fields (Shirazi & Behzadan, 2015). Moreover, systematic reviews that follow PRISMA principles and PICOS frameworks not only show how immersive technologies can improve learning outcomes, but they also stress how these technologies can help connect policy directions with what happens in the classroom (Tene et al., 2024).

The Concept of Metaverse and Its Applications in STEM Education

The Metaverse, which Neal Stephenson first thought about in his 1992 book, has gone from being a literary vision to an actual technological goal thanks to improvements in virtual reality (VR), augmented reality (AR), and blockchain technology (Chen et al., 2024). This "post-reality cosmos" merges physical and digital realms into a persistent, multi-user environment, offering a continuous and enduring virtual experience. Users interact through avatars and co-create experiences analogous to real-world social activities, fostering a participatory and engaging digital ecosystem (Almeman et al., 2025).

The Metaverse is a network of real-time 3D virtual worlds that are all connected. It lets people communicate with each other in a wide range of ways and have digital identities that last forever. By integrating virtual, augmented, and mixed realities, and enhancing experiences with haptic feedback and other sensory technologies, it allows users to interact with digital objects and each other in real-time, creating a profound sense of presence (Huynh-The et al., 2023). While definitions vary across disciplines, common conceptualizations emphasize a three-dimensional online environment where users represented by avatars engage in social, economic, and educational activities within a persistent, immersive digital realm (Dwivedi et al., 2022). This distinguishes the Metaverse from conventional VR systems and digital twins, which primarily focus on simulated interfaces or replication of real-world assets (Tu & Silva, 2025).

The incorporation of the Metaverse into STEM education signifies a substantial educational advancement (Lin et al., 2022). Leveraging VR, AR, and 3D technologies, it facilitates a transition from traditional classrooms to dynamic, immersive virtual environments (Almeman et al., 2025). Students can conduct experiments in virtual laboratories, explore engineering designs in 3D, simulate mathematical models dynamically, and engage in collaborative project-based learning without the limitations of safety, logistics, or physical infrastructure (Zhang et al., 2022). These immersive experiences encourage active engagement, higher-order thinking skills like analysis, synthesis, and assessment, and a better grasp of difficult STEM concepts.

Beyond practical simulations, the Metaverse supports personalized learning pathways and adaptive assessments tailored to individual student needs, moving past standardized testing (Onu et al., 2023). It also enhances social learning by enabling interaction with peers and instructors in shared virtual spaces, which is critical for teamwork-based problem-solving in STEM fields (Chen et al., 2024). Immersive technologies integrated onto these platforms have regularly demonstrated enhancements in student engagement, motivation, creativity, and skill learning (Tene et al., 2024).

Moreover, the Metaverse bridges the gap between digital policy frameworks and classroom practice, facilitating alignment with global educational goals such as digital literacy, accessibility, and 21st-century competency development (Dahan et al., 2022). By combining physical and virtual realities in shared 3D environments, it moves beyond conventional e-learning systems to offer deeper immersion, interactivity, and real-world relevance, fostering a comprehensive, participatory, and adaptive STEM learning ecosystem (Almeman et al., 2025).

This combination of immersive technology not only solves the logistical and moral problems that traditional labs have, but it also offers scalable solutions for making sure that everyone has access to high-quality educational experiences. Students cultivate essential competencies in critical thinking, problem-solving, teamwork, and creativity required for 21st-century STEM careers through these immersive, interactive, and adaptable virtual environments (Onu et al., 2023). The Metaverse thus represents a transformative paradigm, converging technological innovation with pedagogical practice to redefine STEM education for contemporary and future learners (Chen et al., 2024).

STEM Learning Experiences through Augmented Reality (AR)

Augmented Reality (AR) is the use of mobile devices, wearable technology, or head-mounted displays to add digital material, including 3D objects, animations, or simulations, to real-world settings (Lastrucci et al., 2024; Sulak & Koklu, 2024). By overlaying virtual objects onto physical surroundings in real-time, AR enables learners to perceive, interact with, and manipulate digital information within authentic contexts (Sommerauer & Müller, 2014). Unlike Virtual Reality, which fully immerses users in synthetic worlds, AR enhances reality, providing a bridge between abstract concepts and tangible experiences. This affordance makes AR particularly suitable for education, as it facilitates experiential learning, conceptual visualization, and engagement with otherwise intangible or complex phenomena (Kim & Choi, 2025).

AR transforms traditional pedagogical approaches by providing interactive experiences that merge digital and physical learning environments (Chin et al., 2020). For instance, students can visualize molecular structures in chemistry, simulate astronomical models in physics, or manipulate 3D engineering designs, thereby enhancing both understanding and retention of STEM concepts (Ibáñez & Kloos, 2018; Mystakidis et al., 2021). By promoting active involvement, AR motivates learners to transition from passive knowledge absorption to experiential exploration, thereby cultivating higher-order cognitive skills including analysis, synthesis, and assessment (Palada et al., 2024).

Recent improvements in mobile technology, such as high-resolution cameras, advanced sensors, and wearable devices, have made AR available to everyone allowing it to move beyond specialized laboratory contexts into everyday classrooms (Marín et al., 2023). AR applications can support collaborative learning, enabling groups of students to jointly manipulate digital objects and engage in problem-solving activities (Lunding et al, 2023). Furthermore, gamified AR experiences and tangible interfaces increase motivation, curiosity, and engagement, particularly in younger learners or abstract disciplines like chemistry (Tene et al., 2024).

The integration of AR into STEM education also addresses the challenges of remote and resource-limited learning environments. Virtual laboratories, enabled through AR, allow safe experimentation and repeated practice without the constraints of physical materials or risk (Iqbal & Campbell, 2022). Such platforms support constructivist learning by permitting learners to test hypotheses, observe outcomes, and iteratively refine their understanding in a controlled, interactive environment. These experiences cultivate metacognitive skills, expert thinking, and decision-making capabilities essential for professional development in scientific and engineering disciplines (Kalemkuş & Kalemkuş, 2024).

In addition, AR fosters spatial reasoning and visualization skills, critical for STEM disciplines where manipulating 3D structures and understanding abstract relationships are essential (Akçayır & Akçayır, 2016). Augmented reality (AR) lets learners directly interact with complicated systems by putting digital models on top of real-world situations. This closes the gap between theory and practice (Özçakır & Çakıroğlu, 2021). This immersive capability encourages active participation, lessens cognitive load, and improves accessibility, which supports different ways of learning and encourages inclusive teaching methods (Lampropoulos et al., 2022).

Empirical evidence demonstrates that AR-based STEM learning improves student motivation, engagement, and performance across multiple disciplines. For example, AR applications in engineering enhance collaborative problem-solving, enable exploration of intricate machine designs, and facilitate the comprehension of complex scientific phenomena (Suhail et al., 2024). In chemistry and biology, AR simulations allow learners to conduct experiments, manipulate molecular models, and explore anatomical structures safely, providing repeated and scaffolded practice that strengthens both conceptual and procedural knowledge (Mansour et al., 2024).

Moreover, AR supports teacher professional development by offering immersive platforms for training and curriculum experimentation, enabling educators to refine instructional strategies, integrate interactive content, and enhance student engagement (Suhail et al., 2024). The blend of interactive visualizations, chances to work together, and gamified experiences makes AR a powerful tool for teaching 21st-century skills including critical thinking, problem-solving, creativity, and teamwork (Petrov & Atanasova, 2020).

In summary, the integration of Augmented Reality technologies in STEM education represents a paradigm shift in teaching and learning. AR combines real and virtual worlds to provide immersive, interactive, and personalized learning experiences that improve understanding of concepts, increase engagement, and develop important cognitive and metacognitive skills. Through safe experimentation, collaborative problem-solving, and dynamic visualization, AR empowers learners to engage deeply with complex STEM concepts, laying the foundation for both academic achievement and professional competence in the 21st century (AlGerafi et al., 2023).

Pedagogical Impacts and Learning Outcomes

Tene et al. (2024) say that immersive technologies, like Augmented Reality (AR), Virtual Reality (VR), and mixed reality, have changed STEM education over time by making it more engaging, collaborative, and hands-on. These technologies allow learners to engage with abstract and complex concepts in ways that transcend traditional classroom limitations, enhancing comprehension, engagement, and skill acquisition. For instance, augmented reality (AR) adds digital information to the real world, allowing students to work with 3D models and see how complicated processes work. Virtual reality (VR) and Metaverse platforms, on the other hand, provide fully immersive spaces for trying things out and solving problems (AlGerafi et al., 2023).

One of the most important effects of modern technologies on teaching is that they encourage students to work together and talk to each other. AR applications facilitate group exploration of digital objects, whereas Metaverse environments provide shared virtual spaces for collaborative project design, discussion, and reflection (Tene et al., 2024). This interaction supports the development of teamwork, communication, and social learning skills, essential competencies for modern STEM education. Evidence indicates that immersive technology can substantially improve collaborative problem-solving by enabling learners to model real-world situations and share ideas in ways that are challenging to replicate in conventional classrooms (Mansour et al., 2024).

In addition to collaboration, immersive technologies foster active learning and student engagement. By integrating simulations, gamified tasks, and interactive modules, students move from passive knowledge reception to active participation, which promotes critical thinking and knowledge retention (AlGerafi et al., 2023; Bermejo et al., 2023). Studies indicate that AR and VR reduce cognitive load, making abstract scientific and mathematical concepts more accessible, while simultaneously increasing learner motivation and imaginative capabilities (Tene et al., 2024). For younger learners, AR-supported activities provide scaffolding and visualizations that facilitate comprehension and encourage the construction and revision of mental models (Koklu & Sulak, 2021).

The cultivation of scientific process skills and problem-solving abilities is an essential aspect of STEM education. Immersive technology allow students to do experiments that would be dangerous, expensive, or impossible to do in a regular lab (Tene et al., 2024). Virtual laboratories provide dynamic, secure, and interactive settings in which learners can change variables, employ measurement instruments, and monitor outcomes in real time (Abdelmoneim et al., 2022). This hands-on method promotes a constructivist learning framework, cultivating metacognitive skills, expert reasoning, and iterative problem-solving capabilities that emulate professional scientific investigation (Kalemkuş & Kalemkuş, 2024). Such experiences enhance students' ability to transfer knowledge, make informed decisions, and develop confidence in applying STEM concepts across disciplines.

Furthermore, immersive technologies facilitate assessment and learning analytics opportunities. Digital platforms embedded within AR, VR, and Metaverse environments can track student interactions, engagement patterns, and problem-solving strategies, enabling personalized feedback and adaptive learning (Suhail et al., 2024; Halim & Ismail, 2025). These analytics tools allow educators to move beyond traditional summative assessments by capturing a broader range of learning behaviors and outcomes, such as collaboration, decision-making, and experimental exploration (Suhail et al., 2024). By combining immersive experiences with learning analytics, instructors can tailor interventions, monitor skill development, and identify areas where students may require additional support.

Immersive technologies also support visualization and spatial reasoning, which are critical for STEM disciplines. The ability to manipulate 3D structures in virtual or augmented environments allows students to understand complex molecular, anatomical, or engineering systems more intuitively (Sviridova et al., 2023). For instance, AR applications enable learners to superimpose anatomical models onto physical space, facilitating exploration and comprehension of spatial relationships, while VR-based simulations replicate laboratory processes in a risk-free environment (Almeman et al., 2025). Such experiences contribute not only to cognitive gains but also to motivational and affective outcomes, as learners engage more fully with immersive content.

The incorporation of the Metaverse and AR into educational systems signifies a transformative transformation that facilitates contextualized, individualized, and cooperative learning experiences. These technologies can simulate real-world challenges, providing students with authentic problem-solving opportunities that strengthen STEM skills and cognitive flexibility (Thangavel, 2025). The immersive nature of these platforms also facilitates adaptive learning, allowing students with varying prior knowledge, learning styles, and skill levels to engage meaningfully with complex concepts (Poupard et al., 2025). Research underscores the importance of evaluating these technologies not only for engagement but also for long-term learning outcomes, emphasizing knowledge retention, skill transfer, and motivation as key indicators of success (Cao & Yu, 2023; Shankar, 2023).

Another notable pedagogical advantage is enhanced accessibility. Virtual laboratories and AR modules provide equitable learning opportunities for students in remote or underserved areas, ensuring continued access to high-quality STEM experiences (Ananikov, 2024). These platforms allow learners to experiment repeatedly, receive immediate feedback, and develop competence in areas where physical resources may be limited (Abdelmoneim et al., 2022). Additionally, immersive technologies encourage learner autonomy, self-confidence, and reflective practice, which are crucial for lifelong learning in STEM disciplines (Kalemkuş & Kalemkuş, 2024).

Research consistently demonstrates that immersive technologies improve academic performance. AR and VR interventions in STEM have shown positive effects on test scores, conceptual understanding, and applied skill development (Bermejo et al., 2023). Mixed reality and virtual simulations improve lab abilities, help people see scientific phenomena, and make people more interested in the material (Petrov & Atanasova, 2020). Moreover, these technologies foster creativity and innovation, allowing students to explore alternative solutions and construct knowledge in ways that conventional methods cannot support (Tene et al., 2024).

Challenges and considerations remain, particularly in terms of instructional design and technology adoption. While the potential for improved outcomes is substantial, teachers must be adequately trained to integrate AR, VR, and Metaverse tools effectively (Thangavel, 2025). Without sufficient training and pedagogical support, there is a risk of superficial implementation or underutilization. Additionally, technical limitations, costs, and infrastructure requirements may pose barriers to widespread adoption, particularly in schools with limited resources (Mondal & Mondal, 2025). Ensuring equitable access and addressing data privacy, cybersecurity, and digital well-being are critical considerations that educators and policymakers must address (Onu et al., 2023).

Finally, immersive technologies provide opportunities for future research. Studies should investigate long-term learning outcomes, the effectiveness of AI-driven personalized instruction, and the development of inclusive policies for equitable access (Tene et al., 2024). Research is also needed to examine how adaptive learning models within AR and Metaverse environments can cater to individual student needs across diverse educational contexts and disciplines (Zhang et al., 2022). Longitudinal studies assessing cognitive and non-cognitive outcomes, as well as the efficacy of immersive technologies in promoting collaboration, critical thinking, and problem-solving, will provide robust evidence for informed integration into STEM education (Onu et al., 2023).

In conclusion, incorporating AR, VR, and Metaverse technologies into STEM education offers significant pedagogical advantages, such as increased engagement, active learning, collaboration, skill enhancement, and evaluation opportunities. When used carefully and with the help of professional development, these immersive platforms could change the way we teach, make learning better, and get students ready for the complicated scientific and technological problems they will face in the future (Tene et al., 2024). Addressing challenges such as technical barriers, instructional design, and ethical considerations will be crucial to maximize the effectiveness and sustainability of these innovations in diverse educational contexts.

The Role of Educators and Digital Competencies

The successful integration of Metaverse and Augmented Reality into STEM education depends largely on the digital competencies and pedagogical readiness of educators. Teachers are not only facilitators of knowledge but also designers of learning experiences who must adapt instructional strategies to effectively leverage immersive technologies (Chiu & Li, 2023). This requires educators to go beyond technical proficiency and develop a pedagogical vision for how technologies can enhance inquiry, collaboration, and creativity. This encompasses developing skills in creating and editing digital content, understanding the educational advantages and challenges of AR integration, and employing effective pedagogical strategies to foster digital competencies (Baltynova et al., 2023) This requires a thorough comprehension of the integration of AR and VR into pedagogical approaches, the advancement of digital literacy among students, and the cultivation of critical thinking through technological interaction (Taggart et al., 2023). Nonetheless, obstacles such infrastructural deficiencies, fiscal limitations, and the necessity for extensive teacher training must be confronted to promote the extensive integration of these technologies in educational environments (Tene et al., 2024). To address these challenges, specialized professional development programs are crucial, providing educators with the requisite technological expertise and pedagogical strategies to effectively engage with immersive environments (Chiu & Li, 2023). Even though more and more people are interested in using immersive technologies in education, there isn't yet a comprehensive technique for teaching future STEM teachers how to use augmented reality in educational resources (Kiv et al., 2023). While significant research explores the impact of AR on student learning, studies focusing on teacher training and perceptions regarding AR implementation are notably scarce (Marín et al., 2023). This gap underscores the imperative for additional research into methodologies for teacher professional development and the augmentation of digital literacy, especially concerning the advent of emerging immersive technologies. Many teachers do not feel ready or do not have the skills they need to use technology effectively in the classroom. This shows a big gap between the need for technology and the readiness of teachers (Silva-Díaz et al., 2023). Therefore, addressing the need for teachers to integrate AR, VR, and mixed reality for real-life learning experiences is crucial for initial teacher education. Teacher education programs and policymakers should thus contemplate the integration of immersive experiences utilizing VR and AR to enhance pre-service teachers' understanding and assessment of their capacity to facilitate learning. This proactive strategy can cultivate heightened curiosity and a readiness to investigate innovative ICT practices among educators, as well as an acknowledgment of the importance of enhancing their digital competencies (Taggart et al., 2023).

The incorporation of immersive technologies, including Augmented Reality and the Metaverse, into STEM education represents a significant evolution in educational methodologies, requiring a robust framework for its execution (Tene et al., 2024). This integration demands not only an understanding of the technological tools themselves but also a nuanced appreciation for how they can fundamentally reshape content delivery and pedagogical strategies within STEM disciplines. The TPACK framework offers a robust conceptual model for understanding and guiding this integration, particularly by emphasizing the intricate interplay among technology, pedagogy, and content knowledge (Rahmawati et al., 2021). This framework provides a critical lens for educators to move beyond superficial technological adoption towards a deeper, more intentional integration that enhances student learning outcomes (Tene et al., 2024). The TPACK framework asserts that successful technology integration in education results from the dynamic interplay of these three fundamental knowledge domains, rather than their discrete application. This holistic approach is crucial for leveraging the full potential of AR and Metaverse tools, ensuring they are employed in ways that are both technologically sound and pedagogically effective (Bwalya et al., 2023). The framework underscores that teachers must possess a sophisticated blend of these knowledge domains to effectively design and implement learning experiences that transcend traditional boundaries, particularly when incorporating novel immersive technologies (Hsu et al., 2023). This involves developing specialized teacher competencies for utilizing AR in subjects like physics and creating VR-based educational tools for complex concepts such as projectile motion, as noted by recent research (Tene et al., 2024). As a result, it is very important to help teachers develop their design thinking abilities so that they can use AR in a meaningful way. This will allow them to creatively get around obstacles by changing or creating lesson plans and activities that are appropriate for different learning situations (Hsu et al., 2023). This thorough understanding guarantees that technology acts as a facilitator for profound learning, rather than simply as a pedagogical tool (Jimoyiannis, 2010). The TPACK framework, by delineating the complex relationships between these knowledge domains, offers a structured approach to address the challenges of integrating advanced digital technologies in education. This perspective highlights that merely understanding how a technology operates is insufficient; educators must also grasp its affordances for enriching instruction and promoting deeper learning (Michałko et al., 2022).

The swift advancement of immersive technologies, such as virtual reality, augmented reality, and mixed reality, offers unparalleled opportunities and considerable obstacles for contemporary education. These technologies present novel instructional methodologies that can augment student involvement, promote experiential learning, and grant access to hitherto unattainable situations (Taggart et al., 2023). However, to fully leverage their potential, educators require comprehensive professional development that extends beyond technical proficiency to encompass pedagogical integration and critical ethical considerations (Schwaiger et al., 2024). This involves providing teachers with both the technical abilities and the pedagogical content understanding essential for the efficient integration of these tools into their courses (Taggart et al., 2023). In addition, good professional development programs should not only teach teachers about the technical and pedagogical elements of new technologies, but also on the moral issues that come with them. This will help teachers teach pupils how to use them responsibly (Brandão et al., 2024). Moreover, professional development can empower educators to adapt to dynamic educational landscapes and address the evolving needs of their students, particularly concerning technological advancements (Mouta et al., 2024). Furthermore, professional development is crucial for enhancing educators' confidence and proficiency in utilizing these tools. Studies indicate that educators trained in immersive technology are more inclined to adopt new methodologies and promote favorable educational outcomes (Boel et al., 2023). Additionally, teachers must be aware of ethical and socio-cultural considerations, such as ensuring equitable access, safeguarding student data, and addressing potential issues of digital addiction or distraction (Schwaiger et al., 2024). Such comprehensive professional learning opportunities should be evidence-informed, long-lasting, contextualized, and team-oriented to maximize their effectiveness in promoting implementation and sustained use (Love et al., 2020). A crucial aspect of this preparation involves addressing the inherent technical demands of virtual learning environments and ensuring educators possess the specialized skills and resources for their effective design and implementation (Karcher et al., 2023).

This evolution requires a thorough comprehension of the strategic implementation of immersive technologies to enhance engagement, critical thinking, and collaborative problem-solving in scientific and technical fields. The successful integration of AR and Metaverse in STEM education hinges on educators' capacity to move beyond traditional teaching paradigms, embracing innovative pedagogical approaches that leverage the unique affordances of these technologies (Tene et al., 2024). This requires not only technical proficiency but also a refined pedagogical understanding to effectively bridge the gap between virtual enhancements and tangible learning outcomes (Velarde-Camaqui et al., 2024). The educational prospects within the Metaverse are extensive, offering virtual environments that can significantly enrich learning experiences through interactive modeling and experiential learning (Chen et al., 2024). These immersive technologies, such as augmented reality and virtual reality, make it possible to create realistic situations for complicated lab experiments or virtual field trips that would be too dangerous or hard to get to in real life (Tene et al., 2024). The metaverse, envisioned as an expansive digital ecosystem, enables individuals to transition from physical to virtual environments, demonstrating significant utility in educational contexts where practical experiments are difficult or perilous, such as space exploration, chemical experimentation, and flight simulation training (Almeman et al., 2025). This integration makes it possible to make complex, interactive learning spaces that give students hands-on experiences, which makes them more interested in and understand the material (Schwaiger et al., 2024). Moreover, the immersive features of AR and the Metaverse present unparalleled prospects for customized learning pathways, according to specific student requirements and learning preferences through individualized challenges and immediate feedback (Tene et al., 2024). These virtual platforms facilitate experiential learning, permitting students to investigate and engage in intricate, genuine tasks that are frequently inaccessible in the physical realm (Almeman et al., 2025).

Challenges, Limitations, and Ethical Considerations

Even though Augmented Reality (AR) and the Metaverse are known to have the potential to change STEM education by providing immersive and interactive learning experiences, there are still big problems that make it hard for them to be used widely and for a long time (Tene et al., 2024). These impediments encompass high implementation costs, inherent technical limitations, and notable resistance among educators to adopt these novel technologies (Thangavel, 2025). This resistance often stems from concerns regarding instructional design, increased workload, and a perceived lack of institutional support (Hsu et al., 2023). Moreover, the absence of standardized platforms and the considerable effort required for customizing virtual environments further complicate the adoption of AR/VR tools within educational frameworks (Terkaj et al., 2024).

A primary challenge involves the infrastructure and accessibility required for AR and Metaverse applications. High-performance hardware, reliable high-bandwidth networks, cloud storage solutions, and skilled personnel are essential for effective deployment, yet they impose significant financial and operational burdens on institutions, particularly in underserved regions (Huang & Tseng, 2025). Additionally, developing high-quality, curriculum-aligned AR/VR content requires expertise in 3D modeling, instructional design, and pedagogy, a process often constrained by time and resource limitations (Cabrera-Duffaut et al., 2024). This scarcity of tailored educational content frequently forces educators to adapt generic software or create bespoke solutions, both of which present substantial challenges.

Privacy, security, and digital ethics constitute another critical dimension of concern. AR and Metaverse applications collect large volumes of personal and behavioral data, necessitating robust safeguards to ensure compliance with data protection regulations such as GDPR or FERPA (Raman et al., 2025). The immersive and social nature of these environments introduces risks including identity misuse, exposure to harassment, and potential addiction, especially among younger learners (Zhang et al., 2022; Ramolia et al., 2024). Addressing these concerns requires comprehensive ethical frameworks, clear regulatory guidelines, and technological solutions such as blockchain for data traceability (Onu et al., 2023).

From a pedagogical standpoint, educators frequently encounter reluctance stemming from insufficient training and a lack of experience with AR/VR integration (Tene et al., 2024). To help teachers create and carry out immersive learning experiences, they need to have the right technical skills, pedagogical content understanding, and digital literacy. This is why effective professional development programs are so important (Schwaiger et al., 2024). These programs should also address ethical considerations, including equitable access, responsible use, and fostering safe collaborative environments (Brandão et al., 2024).

Furthermore, the digital divide remains a persistent limitation. Variations in institutional funding, access to reliable infrastructure, and availability of immersive content exacerbate inequities in STEM education, limiting opportunities for students in resource-constrained contexts (Silva-Díaz et al., 2023). Research indicates that despite the demonstrated benefits of AR and Metaverse platforms—including enhanced engagement, collaboration, and knowledge retention—these advantages may be unevenly realized without targeted interventions and institutional support (AlGerafi et al., 2023).

In sum, while AR and Metaverse technologies offer transformative opportunities for STEM education, their effective and equitable integration depends on addressing infrastructural, pedagogical, and ethical challenges. Future efforts should prioritize professional development, accessible content creation tools, standardized platforms, and rigorous data protection measures to ensure that these immersive environments can sustainably enhance learning outcomes (Qiu et al., 2023).

Conclusion and Future Research Directions

This chapter delves into the multifaceted benefits and challenges associated with integrating immersive technologies, specifically the Metaverse and Augmented Reality, into STEM education. This integration holds substantial promise for revolutionizing traditional pedagogical approaches by fostering dynamic and interactive learning environments (Tene et al., 2024). Augmented reality has become a popular technology, and researchers often look into how it might help students stay interested and do better in school. Studies show that immersive technologies like AR and VR make it much easier to understand difficult ideas, boost student engagement, and make group learning more interesting (Tene et al., 2024). Moreover, integrating social and ethical values into education has been highlighted as essential for fostering students' holistic development (Ergün Kaplan & Sulak, 2017). These technologies facilitate active learning through simulations and interactive experiences, promoting critical thinking and knowledge retention across diverse educational domains (AlGerafi et al., 2023). Furthermore, AR's capability to overlay digital information onto the real world allows for powerful visualization of abstract scientific and mathematical concepts, particularly in engineering education, where deep knowledge and problem-solving skills are paramount (Suhail et al., 2024). This immersive approach has been shown to enhance academic performance and increase proficiency in STEM capabilities by providing hands-on learning experiences. Specifically, AR reduces cognitive load and enhances imaginative capabilities, making complex scientific fundamentals more accessible and engaging for learners. The utility of AR extends beyond visualization, enabling gamified and collaborative learning experiences, particularly within primary school curricula (Tene et al., 2024). The broader application of both Augmented Reality and Virtual Reality across educational levels underscores their capacity to foster better knowledge retention and skill development in fields ranging from medicine to language learning, despite existing limitations such as high costs and technical constraints (Thangavel, 2025).

Even if these technologies have a lot of potential, there are still problems with interoperability, standardization, and the need for more solid proof of their effectiveness. This means that further research and development are needed to make sure that these technologies have a place in education (Onu et al., 2023). Moreover, significant barriers impede widespread adoption, including high implementation costs, inherent technical limitations, and resistance among educators due to concerns about instructional design, increased workload, and perceived lack of institutional support (Thangavel, 2025). The absence of standardized platforms and the substantial effort required to customize virtual environments further complicate the integration of AR/VR tools within educational frameworks (Terkaj et al., 2024).

The swift advancement of immersive technologies demands a comprehensive examination of their enduring impacts on student learning and development, including cognitive aspects such as knowledge acquisition and retention, as well as non-cognitive elements like motivation and engagement (Raman et al., 2025). Previous meta-analyses indicate that AR positively influences learning outcomes, particularly when considering spatial abilities (Cao & Yu, 2023). Beyond initial engagement, immersive platforms foster improved knowledge retention and practical skill development by transporting students to virtual environments that facilitate experiential learning (Shankar, 2023). Initial research on the Metaverse underscores the necessity of investigating students' sense of presence and the emotional dimensions linked to immersive experiences, transcending mere cognitive outcomes (Çelik & Baturay, 2023; Jung et al., 2023). Subsequent study ought to investigate the relationship between cognitive load reduction and tangible learning outcomes, individual variances including prior knowledge and learning preferences, as well as the versatility of immersive technology across many academic disciplines (Poupard et al., 2025).

Future study should investigate the long-term educational outcomes of integrating AR and the Metaverse, the impact of AI-driven personalization, and the formulation of inclusive policies to guarantee fair access. When designing a curriculum, it's important to think about ways to make it last that are in line with national education goals. Subsequent inquiries ought to examine adaptive educational frameworks that utilize immersive technologies beyond simple interactive instruments, emphasizing tailored learning experiences that address the unique demands and preferences of each student (Tene et al., 2024). Additionally, the efficacy of Metaverse applications in educational settings, particularly regarding interoperability and standardized content development, requires further empirical validation (Onu et al., 2023). Longitudinal research are crucial for evaluating the enduring effects of AR and the Metaverse on cognitive and non-cognitive characteristics across various age groups and educational levels (Zhang et al., 2022).

In sum, the integration of AR and the Metaverse into STEM education presents transformative opportunities to foster immersive, interactive, and engaging learning experiences, while simultaneously posing infrastructural, pedagogical, and ethical challenges. It is important for educators, policymakers, and industry leaders to work together to create strong teaching frameworks and thorough teacher training programs. This will make sure that these immersive technologies live up to their potential to improve student learning outcomes in a variety of educational settings (Thangavel, 2025).

References

Abdelmoneim, R., Hassounah, E., & Radwan, E. (2022). Effectiveness of virtual laboratories on developing expert thinking and decision-making skills among female school students in Palestine. *Eurasia Journal of Mathematics Science and Technology Education*, *18*(12). https://doi.org/10.29333/ejmste/12708

Aguilera, D., Lupiáñez, J. L., González, J. M. V., & Palacios, F. J. P. (2021). In search of a long-awaited consensus on disciplinary integration in STEM education. *Mathematics*, *9*(6), 597. https://doi.org/10.3390/math9060597

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, *20*, 1-11. https://doi.org/10.1016/j.edurev.2016.11.002

AlGerafi, M. A. M., Zhou, Y., Oubibi, M., & Wijaya, T. T. (2023). Unlocking the potential: A comprehensive evaluation of augmented reality and virtual reality in education. *Electronics*, *12*(18), 3953. https://doi.org/10.3390/electronics12183953

Almeman, K., Ayeb, F. E., Berrima, M., Issaoui, B., & Morsy, H. (2025). The integration of AI and metaverse in education: A Systematic Literature Review. *Applied Sciences*, *15*(2), 863. https://doi.org/10.3390/app15020863

Ananikov, V. P. (2024). Top 20 influential AI-based technologies in chemistry. *Artificial Intelligence Chemistry*, *2*(2), 100075. https://doi.org/10.1016/j.aichem.2024.100075

Baltynova, A., Kamariyash, K., Muzdbaeva, T., Bolat, Y., Beleukhanova, K., Zharikova, D., & Mollakuqe, E. (2023). Pedagogical conditions for the training of future teachers based on digital educational technologies. *International Journal of Emerging Technologies in Learning (iJET)*, *18*(18), 121. https://doi.org/10.3991/ijet.v18i18.43209

Bermejo, B. G., Juiz, C., Cortes, D., Oskam, J., Moilanen, T., Loijas, J., Govender, P., Hussey, J., Schmidt, A. L., Burbach, R., King, D. B., O'Connor, C., & Dunlea, D. (2023). AR/VR teaching-learning experiences in higher education institutions (HEI): A systematic literature review. *Informatics*, *10*(2), 45. https://doi.org/10.3390/informatics10020045

Boel, C., Dekeyser, K., Lemal, M., Rotsaert, T., Valcke, M., Schellens, T., & Struyf, D. (2023). Towards a framework for a nation-wide implementation of augmented, virtual and mixed reality in K-12 technical and vocational education. *TechTrends*, *68*(2), 295. https://doi.org/10.1007/s11528-023-00925-y

Brandão, A., Pedro, L., & Zagalo, N. (2024). Teacher professional development for a future with generative artificial intelligence – an integrative literature review. *Digital Education Review*, *45*, 151. https://doi.org/10.1344/der.2024.45.151-157

Bwalya, A., Rutegwa, M., Tukahabwa, D., & Mapulanga, T. (2023). Enhancing pre-service biology teachers' technological pedagogical content knowledge through a tpack-based technology integration course. *Journal of Baltic Science Education*, *22*(6), 956. https://doi.org/10.33225/jbse/23.22.956

Cabrera-Duffaut, A., Llorente, A. M. P., & Rodríguez, A. I. (2024). Immersive learning platforms: analyzing virtual reality contribution to competence development in higher education—a systematic literature review. *Frontiers in Education*, *9*. https://doi.org/10.3389/feduc.2024.1391560

Cañavate, J., Martinez-Marroquin, E., & Colom, X. (2025). Engineering a sustainable future through the integration of generative ai in engineering education. *Sustainability*, *17*(7), 3201. https://doi.org/10.3390/su17073201

Cao, W., & Yu, Z. (2023). The impact of augmented reality on student attitudes, motivation, and learning achievements—a meta-analysis (2016–2023). *Humanities and Social Sciences Communications*, *10*(1). https://doi.org/10.1057/s41599-023-01852-2

Çelik, F., & Baturay, M. H. (2024). The effect of metaverse on L2 vocabulary learning, retention, student engagement, presence, and community feeling. *BMC Psychology*, *12*(1), 58. https://doi.org/10.21203/rs.3.rs-3763892/v1

Chen, G., Jin, Y., & Chen, P. (2024). Development of a platform for state online education services: Design concept based on meta-universe. *Education and Information Technologies*, *29*(17), 23605. https://doi.org/10.1007/s10639-024-12792-y

Chin, K.-Y., Kao, Y.-C., & Wang, C.-S. (2020). Effects of augmented reality technology in a mobile touring system on university students' learning performance and interest. *Australasian Journal of Educational Technology*, 27. https://doi.org/10.14742/ajet.5841

Chiu, T. K. F., & Li, Y. (2023). How can emerging technologies impact STEM education? *Journal for STEM Education Research*, *6*(3), 375. https://doi.org/10.1007/s41979-023-00113-w

Dahan, N. A., Al-Razgan, M., Al-Laith, A., Alsoufi, M. A., Al-Asaly, M. S., & Alfakih, T. (2022). Metaverse framework: A case study on e-learning environment (ELEM). *Electronics*, *11*(10), 1616. https://doi.org/10.3390/electronics11101616

Dwivedi, Y. K., Hughes, L., Baabdullah, A. M., Ribeiro-Navarrete, S., Giannakis, M., Al-Debei, M. M., Dennehy, D., Metri, B., Buhalis, D., Cheung, C. M. K., Conboy, K., Doyle, R., Dubey, R., Dutot, V., Felix, R., Goyal, D. P., Gustafsson, A., Hinsch, C., Jebabli, I., … Wamba, S. F. (2022). Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. *International Journal of Information Management*, *66*, 102542. https://doi.org/10.1016/j.ijinfomgt.2022.102542

Ergün Kaplan, S. &. Sulak, S. A., (2017). The examination of perception of social values of elementary school students according to different variables. *Bartın University Journal of Faculty of Education, 6(3), 840-858*. https://doi.org/10.14686/buefad.292038

Hsu, H.-P., Cheah, Y. H., & Hughes, J. E. (2023). A case study of a secondary biology teacher's pedagogical reasoning and action with augmented reality technology. *Education Sciences*, *13*(11), 1080. https://doi.org/10.3390/educsci13111080

Huang, T., & Tseng, H. (2025). Extended reality in applied sciences education: A systematic review. *Applied Sciences*, *15*(7), 4038. https://doi.org/10.3390/app15074038

Huynh-The, T., Gadekallu, T. R., Wang, W., Yenduri, G., Ranaweera, P., Pham, Q., Costa, D. B. da, & Liyanage, M. (2023). Blockchain for the metaverse: A Review. *Future Generation Computer Systems*, *143*, 401. Elsevier BV. https://doi.org/10.1016/j.future.2023.02.008

Ibáñez, M. B., & Kloos, C. D. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education*, *123*, 109. https://doi.org/10.1016/j.compedu.2018.05.002

Iqbal, M. Z., & Campbell, A. G. (2022). AGILEST approach: Using machine learning agents to facilitate kinesthetic learning in STEM education through real-time touchless hand interaction. *Telematics and Informatics Reports*, *9*, 100034. https://doi.org/10.1016/j.teler.2022.100034

Irwanto, I. (2021). Research trends in technological pedagogical content knowledge (TPACK): A systematic literature review from 2010 to 2021. *European Journal of Educational Research*, 2045. https://doi.org/10.12973/eu-jer.10.4.2045

Jimoyiannis, A. (2010). Designing and implementing an integrated technological pedagogical science knowledge framework for science teachers professional development. *Computers & Education*, *55*(3), 1259. https://doi.org/10.1016/j.compedu.2010.05.022

Jung, T., Cho, J., Han, D. D., Ahn, S. J., Gupta, M., Das, G., Heo, C. Y., Loureiro, S. M. C., Σιγάλα, M., Trunfio, M., Taylor, A., & Dieck, M. C. tom. (2023). Metaverse for service industries: Future applications, opportunities, challenges and research directions. *Computers in Human Behavior*, *151*, 108039. https://doi.org/10.1016/j.chb.2023.108039

Kalemkuş, J., & Kalemkuş, F. (2024). The effects of designing scientific experiments with visual programming language on learning outcomes. *Science & Education*. https://doi.org/10.1007/s11191-024-00546-8

Karcher, A., Arnold, D., & Kuhlenkötter, B. (2023). Development of a guideline under didactical aspects for the use of immersive virtual learning environments. *Journal of Formative Design in Learning*, *7*(2), 98. https://doi.org/10.1007/s41686-023-00085-5

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education*, *3*(1). https://doi.org/10.1186/s40594-016-0046-z

Kim, J.-Y., & Choi, J. K. (2025). Effects of AR on cognitive processes: An experimental study on object manipulation, eye-tracking, and behavior observation in design education. *Sensors*, *25*(6), 1882. https://doi.org/10.3390/s25061882

Koklu, N., & Sulak, S. A. (2021). World geography with augmented reality. *International Journal of Progressive Sciences and Technologies*, *29*(1), 94-108.

Lampropoulos, G., Keramopoulos, E., Diamantaras, K., & Evangelidis, G. (2022). Augmented reality and gamification in education: A systematic literature review of research, applications, and empirical studies. *Applied Sciences*, *12*(13), 6809. https://doi.org/10.3390/app12136809

Lastrucci, A., Wandael, Y., Barra, A., Ricci, R., Maccioni, G., Pirrera, A., & Giansanti, D. (2024). Exploring augmented reality integration in diagnostic imaging: Myth or reality? *Diagnostics*, *14*(13), 1333. https://doi.org/10.3390/diagnostics14131333

Li, M., & Li, B. (2024). Unravelling the dynamics of technology integration in mathematics education: A structural equation modelling analysis of TPACK components. *Education and Information Technologies*, *29*(17), 23687. https://doi.org/10.1007/s10639-024-12805-w

Lin, H., Wan, S., Gan, W., Chen, J., & Chao, H. (2022). Metaverse in education: Vision, opportunities, and challenges. *2021 IEEE International Conference on Big Data (Big Data)*, 2857. https://doi.org/10.1109/bigdata55660.2022.10021004

Love, M., Simpson, L. A., Golloher, A., Gadus, B., & Dorwin, J. (2020). Professional development to increase teacher capacity for the use of new technologies. *Intervention in School and Clinic*, *56*(2), 115. https://doi.org/10.1177/1053451220914886

Lunding, M. S., Grønbæk, J. E. S., Grymer, N., Wells, T., Houben, S., & Petersen, M. G. (2023). Reality and beyond: proxemics as a lens for designing handheld collaborative augmented reality. *Proceedings of the ACM on Human-Computer Interaction*, *7*, 21. https://doi.org/10.1145/3626463

Lyngdorf, N. E. R., Jiang, D., & Du, X. (2024). Frameworks and models for digital transformation in engineering education: a literature review using a systematic approach. *Education Sciences*, *14*(5), 519. https://doi.org/10.3390/educsci14050519

Mansour, N., Aras, C. Y., Staarman, J. K., & Alotaibi, S. B. (2024). Embodied learning of science concepts through augmented reality technology. *Education and Information Technologies*. https://doi.org/10.1007/s10639-024-13120-0

Marín, J. A. M., López-Belmonte, J., Sánchez, S. P., & Moreno-Guerrero, A.-J. (2023). Attitudes towards the development of good practices with augmented reality in secondary education teachers in Spain. *Technology Knowledge and Learning*, *28*(4), 1443. https://doi.org/10.1007/s10758-023-09671-9

Marzuki, O. F., Lih, E. T. Y., Abdullah, W. N. Z. Z., Khairuddin, N., Inai, N. H., Saad, J. B. M., & Aziz, M. H. A. (2024). Innovating education: A comprehensive review of STEM education approaches. *International Journal of Academic Research in Progressive Education and Development*, *13*(1). https://doi.org/10.6007/ijarped/v13-i1/20490

Michałko, A., Campo, A., Nijs, L., Leman, M., & Dyck, E. V. (2022). Toward a meaningful technology for instrumental music education: Teachers' voice. *Frontiers in Education*, *7*. https://doi.org/10.3389/feduc.2022.1027042

Mondal, H., & Mondal, S. (2025). Adopting augmented reality and virtual reality in medical education in resource-limited settings: constraints and the way forward. *AJP Advances in Physiology Education*. https://doi.org/10.1152/advan.00027.2025

Mouta, A., Sánchez, E. M. T., & Llorente, A. M. P. (2024). Comprehensive professional learning for teacher agency in addressing ethical challenges of AIED: Insights from educational design research. *Education and Information Technologies*. https://doi.org/10.1007/s10639-024-12946-y

Mystakidis, S., Christopoulos, A., & Pellas, N. (2021). A systematic mapping review of augmented reality applications to support STEM learning in higher education. *Education and Information Technologies*, *27*(2), 1883. https://doi.org/10.1007/s10639-021-10682-1

Onu, P., Pradhan, A., & Mbohwa, C. (2023). Potential to use metaverse for future teaching and learning. *Education and Information Technologies*, *29*(7), 8893. https://doi.org/10.1007/s10639-023-12167-9

Özçakır, B., & Çakıroğlu, E. (2021). An augmented reality learning toolkit for fostering spatial ability in mathematics lesson: design and development. *European Journal of Science and Mathematics Education*, *9*(4), 145. https://doi.org/10.30935/scimath/11204

Palada, B., Chandan, V. S., Gowda, C. P., & Nikitha, Prof. (2024). The role of augmented reality (AR) in education. *International Journal for Research in Applied Science and Engineering Technology*, *12*(3), 1400. https://doi.org/10.22214/ijraset.2024.59079

Petrov, P. D., & Atanasova, T. (2020). The effect of augmented reality on students' learning performance in stem education. *Information*, *11*(4), 209. https://doi.org/10.3390/info11040209

Poupard, M., Larrue, F., Sauzéon, H., & Tricot, A. (2025). A systematic review of immersive technologies for education: effects of cognitive load and curiosity state on learning performance. *HAL (Le Centre Pour La Communication Scientifique Directe)*. https://hal.archives-ouvertes.fr/hal-03906797

Qiu, Y., Isusi-Fagoaga, R., & García-Aracil, A. (2023). Perceptions and use of metaverse in higher education: A descriptive study in China and Spain. *Computers and Education Artificial Intelligence*, *5*, 100185. https://doi.org/10.1016/j.caeai.2023.100185

Rahmawati, A., Suryani, N., Akhyar, M., & Sukarmin, S. (2021). Vocational teachers' perspective toward Technological Pedagogical Vocational Knowledge. *Open Engineering*, *11*(1), 390. https://doi.org/10.1515/eng-2021-0040

Raman, R., Kowalski, R. M., & Achuthan, K. (2025). Metaverse technologies and human behavior: insights into engagement, adoption, and ethical challenges. *Computers in Human Behavior Reports*, 100712. https://doi.org/10.1016/j.chbr.2025.100712

Rusmin, L., Misrahayu, Y., Pongpalilu, F., Radiansyah, R., & Dwiyanto, D. (2024). Critical thinking and problem-solving skills in the 21st century. *Deleted Journal*, *1*(5), 144. https://doi.org/10.59613/svhy3576

Schwaiger, M., Krajnčan, M., Vukovič, M., Jenko, M., & Doz, D. (2024). Educators' opinions about VR/AR/XR: An exploratory study. *Education and Information Technologies*. https://doi.org/10.1007/s10639-024-12808-7

Shankar, V. T. A. U. (2023). Impact of virtual reality (vr) and augmented reality (ar) in education. *Tuijin Jishu/Journal of Propulsion Technology*, *44*(4), 1310. https://doi.org/10.52783/tjjpt.v44.i4.1014

Shirazi, A., & Behzadan, A. H. (2015). Content delivery using augmented reality to enhance students' performance in a building design and assembly project. *Advances in Engineering Education*, *4*(3), n3.

Silva-Díaz, F., Carrillo-Rosúa, J., Ferrer, G. F., Carmona, R. M., & Narváez, R. (2023). Valoración de tecnologías inmersivas y enfoque STEM en la formación inicial del profesorado. *RIED Revista Iberoamericana de Educación a Distancia*, *27*(1), 139. https://doi.org/10.5944/ried.27.1.37688

Smith, K., Maynard, N., Berry, A., Stephenson, T., Spiteri, T., Corrigan, D., Mansfield, J., Ellerton, P., & Smith, T. C. (2022). Principles of problem-based learning (pbl) in stem education: using expert wisdom and research to frame educational practice. *Education Sciences*, *12*(10), 728. https://doi.org/10.3390/educsci12100728

Sommerauer, P., & Müller, O. (2014). Augmented reality in informal learning environments: A field experiment in a mathematics exhibition. *Computers & Education*, *79*, 59. https://doi.org/10.1016/j.compedu.2014.07.013

Suhail, N., Bahroun, Z., & Ahmed, V. (2024). Augmented reality in engineering education: enhancing learning and application. *Frontiers in Virtual Reality*, *5*. https://doi.org/10.3389/frvir.2024.1461145

Sulak, S. A., & Koklu, N. (2024). Bibliometric Analysis of Publications Related to Augmented Reality in Education in The Last 20 Years. Advances In Education Sciences. *Advances in Education Sciences, M. Dalkılıç and O. Soslu, Eds. Platanus Publishing, 31-58*. https://doi.org/10.5281/zenodo.14582661

Sviridova, E., Yastrebova, E., Bakirova, G., & Rebrina, F. (2023, October). Immersive technologies as an innovative tool to increase academic success and motivation in higher education. *In Frontiers in Education* (Vol. 8). https://doi.org/10.3389/feduc.2023.1192760

Taggart, S., Roulston, S., Brown, M., Donlon, E., Cowan, P., Farrell, R., & Campbell, A. A. (2023). Virtual and augmented reality and pre-service teachers: Makers from muggles? *Australasian Journal of Educational Technology*, 1. https://doi.org/10.14742/ajet.8610

Tene, T., Tixi, J. A. M., Robalino, M. de L. P., Salazar, M. J. M., Gómez, C.

V., & Bellucci, S. (2024). Integrating immersive technologies with STEM education: a systematic review. *Frontiers in Education*, *9*. Frontiers Media. https://doi.org/10.3389/feduc.2024.1410163

Terkaj, W., Urgo, M., Kovács, P., Tóth, E., & Mondellini, M. (2024). A framework for virtual learning in industrial engineering education: development of a reconfigurable virtual learning factory application. *Virtual Reality*, *28*(3). https://doi.org/10.1007/s10055-024-01042-8

Thangavel, S. (2025). Revolutionizing education through augmented reality (ar) and virtual reality (vr): innovations, challenges and future prospects. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.5195697

Thibaut, L., Ceuppens, S., Loof, H. D., Meester, J. D., Goovaerts, L., Struyf, A., Pauw, J. B., Dehaene, W., Deprez, J., Cock, M. D., Hellinckx, L., Knipprath, H., Langie, G., Struyven, K., Velde, D. van de, Petegem, P. V., & Depaepe, F. (2018). Integrated STEM education: A systematic review of instructional practices in secondary education. *European Journal of STEM Education*, *3*(1). https://doi.org/10.20897/ejsteme/85525

Tu, X., & Silva, B. de C. e. (2025). Are we ready for the metaverse? Implications, legal landscape, and recommendations for responsible development. *Deleted Journal*, *4*(1). https://doi.org/10.1007/s44206-025-00163-0

Velarde-Camaqui, D., Celaya-Ramírez, R., Contreras-Fuentes, Y., & Sanabria-Z, J. (2024). Enhancing STEAM education through augmented reality: the EduAR open platform experience. *Frontiers in Education*, *9*. https://doi.org/10.3389/feduc.2024.1391803

Zhang, X., Chen, Y., Hu, L., & Wang, Y. (2022). The metaverse in education: Definition, framework, features, potential applications, challenges, and future research topics. *Frontiers in psychology*, *13*, 1016300. https://doi.org/10.3389/fpsyg.2022.1016300

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Open Source and Online Platforms in STEM Education

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Chapter Highlights

The following highlights outline the role, structure, and classroom applications of open-source and online platforms in supporting accessible, scalable, and innovative STEM education.

- Defining Open-Source and Online Platforms – Clear distinctions and shared features, emphasizing openness, scalability, and adaptability.
- Open-source and online platforms in STEM education – Importance and significance of open-source and online platforms in STEM education
- Selected Platforms – In-depth discussion of TeachEngineering, NASA STEM Engagement, STEM Learning, and Scientix MOOCs, complemented by PhET, Code.org, and OpenSciEd.
- Practical Applications – Classroom vignettes illustrating how teachers use platforms to overcome barriers in time, pedagogy, assessment, curriculum integration, and professional development.

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Introduction

In recent years, our understanding of education has undergone significant changes in response to global challenges such as climate change and rapid population growth. These forces have given rise to shifting societal needs, compelling education systems to adapt. This rethinking emphasizes not only broader accessibility but also equity. In other words, it ensures that learning opportunities are disseminated fairly and reach those most affected by these challenges. As a result, inclusivity and accessibility have become central to modern educational approaches (Navas-Bonilla et al., 2025). Technologies such as open sources, digital learning tools, and online platforms have played a key role in shaping how education reaches learners (Mexhuani, 2025). STEM education is no exception to this transformation.

STEM education centers on the science, technology, engineering, and mathematics and the integration of these disciplines into real-life contexts (Kelley & Knowles, 2016). This approach aims not only to provide students with scientific knowledge but also to foster the development of interdisciplinary thinking skills (Awad, 2023). In STEM education, engineering occupies a special position, as it not only represents a single discipline but also integrates the others through the engineering design process (English et al., 2017). Thus, mathematics, science, technology, and engineering are not treated as separate domains but rather as an integrated structure aimed at solving real-world problems (Couso & Simmaro, 2020). This integrated approach underscores the need for STEM education to be accessible to a wider audience. Open-source tools and online platforms serve as essential vehicles for linking real-world problem solving with equitable learning opportunities. These tools play a significant role in the development and dissemination of STEM education. They make learning materials more accessible, enable collaboration among teachers and students, and facilitate the rapid sharing of innovative practices (Sanabria-Z. et al., 2024).

Open Source and Online Platforms in Education

Education has transcended the traditional boundaries of the classroom. While knowledge has long been accessible through books and libraries, today learners can even complete entire courses at a distance. Over time, online platforms advanced from static repositories of resources into dynamic ecosystems that promote collaboration, personalization, and assessment (Liu & Yu, 2023). Importantly, these developments paved the way for open-source online platforms, where educational resources and tools are freely accessible to anyone with an internet connection. While distance education laid the groundwork for separating learning from physical classrooms, the early 2000s marked a new stage with the emergence of the Open Educational Resources (OER) movement (Mishra, 2017). The OER philosophy gradually shaped the evolution of online platforms. Whereas traditional distance education mainly relied on institutionally controlled distribution, OER initiatives promoted openness, collaboration, and adaptation across institutional and national boundaries (Li & Wong, 2021; Mishra, 2017). It also led to an important cultural shift: learners were no longer passive recipients of content, but became co-creators by adapting and redistributing materials. This understanding of openness influenced the development of cMOOCs, which emphasized networking, collaboration, and learner autonomy through a connectivist pedagogy. In contrast, xMOOCs are characterized by educator-led instruction and large-scale content delivery, as seen in early platforms like Coursera and edX (Stracke et al., 2019).

To better understand the platforms for STEM education, it is essential to clarify two key terms: open-source platform and online platform. These concepts are sometimes used interchangeably, but they have distinct meanings in the literature. The term open-source platform originates from software development, where open-source refers to making the source code freely available for use, modification, and redistribution (Oussous et al., 2023). In educational contexts, this translates into platforms that not only provide resources but also allow educators to adapt tools to specific pedagogical needs. By contrast, an online platform refers broadly to any web-based environment where learning materials are hosted, distributed, and experienced. Stracke et al. (2019) define online platforms in education through the example of MOOCs, which extend university courses to massive global audiences. Online platforms may be proprietary or open-access, and they can operate on a small or large scale. Their defining feature is that they enable learners and educators to connect through digital environments. In doing so, they often help overcome geographical and temporal boundaries. Open-source platforms emphasize adaptability, freedom to modify, and community-driven development, while online platforms prioritize delivery, scalability, and access (Josué et al., 2023). Openness in education encompasses both technical openness (e.g., open-source code) and content openness (e.g., freely licensed materials), while also serving as a pedagogical value aligned with democratization of knowledge and social justice in education (Sousa et al., 2023). Recognizing these multiple dimensions of openness is essential for understanding how platforms operate within STEM education.

Open-Source and Online Platforms for STEM Education

STEM education has undergone substantial transformations, driven by the dual forces of digital innovation and the need for inclusive, high-quality learning opportunities (Chu, 2025). Online and open-source platforms have emerged as central tools for extending access to STEM disciplines, fostering collaboration, and promoting interdisciplinary problem-solving. These platforms not only deliver content but also provide environments where learners can practice critical thinking, engage in inquiry-based activities, and interact with real-world problems (Dao et al., 2025). STEM education, by its very nature, requires the integration of multiple disciplines. Yet for teachers, achieving pedagogically meaningful integration is not always feasible, as teacher preparation is typically rooted in specialization within a single discipline. Even so, a teacher without formal engineering education and with limited experience in the engineering design process can still implement high-quality STEM activities. Such implementation is facilitated through access to activities provided by open-source and online platforms. These activities may include classroom applications, worksheets, and assessment practices. Moreover, by building on these experiences, teachers may design their own STEM activities, fostering a sustainable approach to STEM education. Nevertheless, it is crucial that teachers have access to appropriate resources. Therefore, in this section, we illustrate how to identify such resources by introducing a set of six criteria used to guide the selection of example technological platforms.

To examine the role of open-source and online platforms in STEM education, it was first necessary to identify exemplary cases of best practices at the global level. These platforms illustrate effective integration of digital tools into teaching and learning. At the same time, they demonstrate potential relevance for diverse educational contexts. To ensure coherence and consistency in the analysis, several criteria were applied in the selection process.

- **Alignment with STEM curricula and standards:** Platforms were selected if they offered resources covering the core STEM subjects, with particular emphasis on facilitating learner interaction. Alignment with established curriculum frameworks ensures that resources can be directly integrated into classroom practice.
- **Free or low-barrier access:** Accessibility is a defining feature of open-source and online platforms. The selected platforms offer their core resources at no cost, thereby reducing barriers for both

teachers and students. This was considered essential to support equitable access across regions with varying levels of educational infrastructure.

- **Pedagogical richness:** Platforms were evaluated based on the degree to which they provide interactive, hands-on, and authentic learning opportunities. Resources that go beyond static text such as simulations, multimedia materials, maker challenges, and project-based activities were prioritized.
- **Support for educators:** Effective adoption of platforms depends on teacher readiness and scaffolding. For this reason, platforms offering professional development, communities of practice, instructional guides, or teacher-focused resources were included. These supports enable teachers to integrate materials into their classrooms more effectively.
- **Global relevance and adaptability:** While the platforms under review were developed in specific national contexts (e.g., United States or United Kingdom), they were selected for their potential to be adapted for international use. Their global reach, flexible structures, and emphasis on fundamental STEM practices make them valuable beyond their original contexts.
- **Evidence of impact and credibility:** Finally, preference was given to platforms with demonstrated effectiveness, credibility, or institutional backing. This includes evidence from usage statistics, evaluations, or recognition by established educational organizations, ensuring that the platforms examined are not only theoretically promising but also practically impactful.

Based on these criteria, four platforms were selected for detailed examination: TeachEngineering, NASA STEM Engagement, STEM Learning (UK), and Scientix MOOCs. Collectively, these platforms represent curriculum support, real-world STEM applications, and professional development opportunities. To broaden the perspective, shorter descriptions of other widely used platforms such as PhET, Code.org, and OpenSciEd will also be included. Although PhET, Code.org, and OpenSciEd met the selection criteria, they were categorized as supplementary platforms. This is because, rather than providing complete STEM lesson plans, they offer educational materials such as simulations and coding activities that can be integrated into STEM lessons. Table 1 presents a comparative overview of these platforms based on key selection criteria, including curriculum alignment, accessibility, pedagogical richness, educator support, global relevance and adaptability, and evidence of impact and credibility.

Table 1. Comparative Analysis of Selected STEM Education Platforms Based on Key Evaluation Criteria

Criteria	TeachEngineering	NASA STEM Engagement	STEM Learning (UK)	Scientix MOOCs	Supplementary Platforms (PhET, Code.org, OpenSciEd)
Curriculum alignment	Next Generation Science Standards (NGSS)-aligned lessons in science and engineering; easy to adapt to other national standards.	Resources linked to U.S. STEM education frameworks-strong focus on space/earth science.	Directly linked to UK National Curriculum in STEM subjects.	Covers STEM-related Professional Development (PD) courses (e.g., citizen science, nature-based solutions); adaptable to general STEM education, though less tied to K–12 curricula.	PhET simulations aligned with science/math; Code.org aligned with Computer Science standards; OpenSciEd aligned with NGSS.
Accessibility	Fully free and open access.	Freely available globally via NASA portal.	Many resources free; some professional development requires fees.	Mostly free MOOCs accessible globally through the Scientix platform.	PhET and Code.org free; OpenSciEd curriculum free.
Pedagogical richness	Hands-on, inquiry-based engineering design challenges. Example: Renewable energy project.	Inquiry- and challenge-based learning with multimedia. Example: NASA Student Challenge on Mars habitats.	Inquiry-based experiments and real-world contexts. Example: Renewable energy lesson pack.	Offers MOOCs on inquiry-based, real-world topics (e.g., citizen science, sustainability).	PhET: interactive simulations; Code.org: Hour of Code activities; OpenSciEd: inquiry-based science units.
Educator support	Teacher guides, rubrics, and background information etc..	Lesson plans, webinars, and educator workshops etc.	Strong Continuing Professional Development, STEM Ambassadors, and online communities.	Explicitly designed for teacher professional development; strong PD focus, resources, and networking.	PhET provides teaching tips; Code.org offers curricula + PD; OpenSciEd provides teacher guides.

Global relevance and adaptability	Open-ended design challenges adaptable worldwide.	Universal appeal of space science; adaptable to international classrooms.	Materials tailored for the UK but adaptable internationally; PD less accessible globally.	Pan-European initiative, globally relevant topics; adaptable internationally but with some EU focus.	PhET widely translated); Code.org global adoption; OpenSciEd adaptable but U.S.-centric.
Evidence of impact and credibility	NSF-supported, widely adopted in U.S. K–12.	Backed by NASA with extensive outreach evaluation.	Government-funded, university- and industry-backed, evaluation studies available.	Backed by European Schoolnet; credible network, though limited published impact studies specific to MOOCs.	PhET validated in research; Code.org widely studied; OpenSciEd backed by major foundations.

As seen in Table 1, the platforms examined in this section illustrate the breadth and diversity of open-source and online tools currently available for STEM education. They meet comprehensive criteria: they align with curricula, provide free or low-barrier access, emphasize interactivity, and offer professional support for educators. Each demonstrates how digital platforms can serve not only as repositories of knowledge but also as ecosystems that connect teachers, students, and communities of practice. At the same time, supplementary platforms such as PhET, Code.org, and OpenSciEd highlight the specialized contributions of narrower initiatives that focus on simulations, computer science, or open science curricula. Taken together, these platforms show how a wide range of digital resources can support STEM learning at different scales and for different purposes. To explore these dynamics in greater detail, the following subsections examine the platforms individually, showcasing how each contributes STEM education.

TeachEngineering

TeachEngineering is a free, open-access digital library developed through collaborations among U.S. universities with support from the National Science Foundation (NSF). It offers more than 1,900 standards-aligned lessons and activities that emphasize engineering design and inquiry learning. All resources are mapped to the NGSS, ensuring pedagogical rigor. Although these resources are designed for U.S. classrooms, the activities are adaptable to international contexts. The platform provides detailed teacher guides, rubrics, and background information, making it a practical tool for classroom use. Its credibility is underscored by NSF funding and wide adoption in K–12 STEM education. TeachEngineering is available at: https://www.teachengineering.org. Figure 1 illustrates the TeachEngineering digital library interface, where educators can browse, standards-aligned lessons, activities, and units by grade level, curriculum type, or subject area.

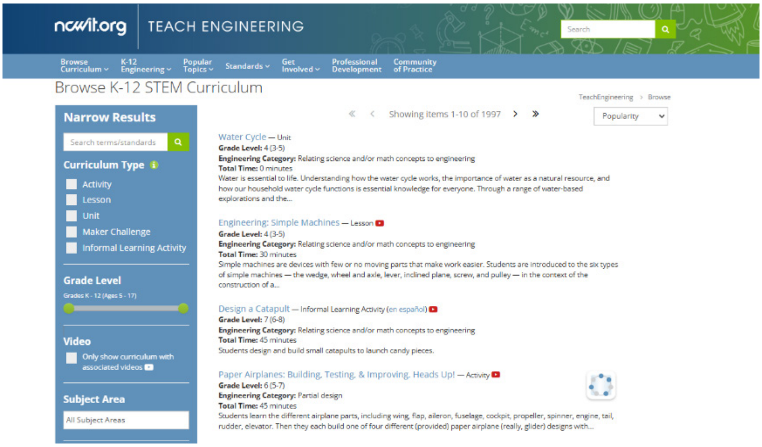

Figure 1. TeachEngineering Interface with Searchable K–12 Stem Resources

NASA STEM Engagement

NASA STEM Engagement provides authentic, mission-based resources that connect students to space exploration, climate science, and robotics. Through simulations, multimedia materials, and inquiry-driven challenges, it fosters curiosity and links classroom learning to real-world scientific endeavors. This platform is particularly significant because it emphasizes examples related to space, climate change, and sustainability, which can foster students' creativity and influence their perspectives on potential future careers. Such an emphasis aligns with the broader objectives of STEM education, as it seeks not only to develop disciplinary knowledge but also to cultivate innovative thinking and awareness of diverse professional pathways. The platform is freely available worldwide and is backed by the authority of NASA, which adds significant credibility. However, its close alignment with U.S. standards and the need for advanced teacher expertise in some areas may limit straightforward adoption internationally. It is accessible via the official website: https://www.nasa.gov/learning-resources/stem-engagement/. Figure 2 shows the NASA STEM Engagement interface, which presents program elements, highlights, and opportunities that connect students with NASA's people, content, and facilities.

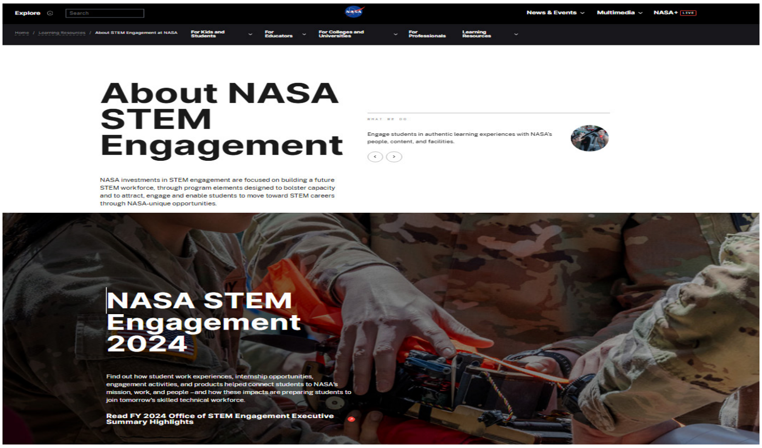

Figure 2. NASA STEM Engagement Platform Interface

STEM Learning

STEM Learning is the largest provider of STEM education support in the UK, offering curriculum-linked teaching resources, professional development opportunities, and access to the STEM Ambassador program. Its strengths lie in its dual focus on classroom practice and teacher professional growth, supported by government and industry partnerships. While many resources are free, some professional development opportunities require payment, and most content is tailored to the UK curriculum. Nevertheless, its adaptable structure and strong emphasis on teacher support make it a valuable resource internationally. It can be accessed at https://www.stem.org.uk/. Figure 3 illustrates the STEM Learning interface, highlighting its focus on professional development and classroom resources.

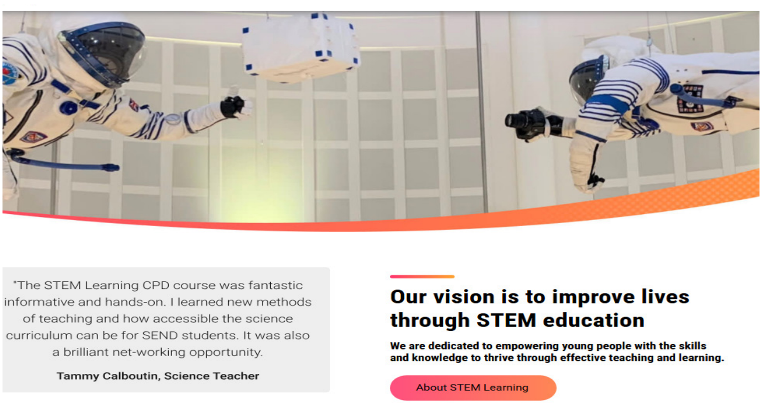

Figure 3. STEM Learning Platform Interface

Scientix MOOCs

Scientix, coordinated by European Schoolnet, supports STEM education across Europe by providing teachers with professional development opportunities through MOOCs. These courses cover contemporary topics such as citizen science, sustainability, and nature-based solutions, helping teachers expand their pedagogical approaches while also enriching their STEM perspective. In addition to supporting classroom strategies, they emphasize science content, technology integration, and activity design, often requiring teachers to create lesson activities that explicitly highlight STEM connections. The platform's global accessibility and European credibility strengthen its appeal, though the MOOCs are often more focused on teacher training than direct K–12 student instruction. Moreover, rather than focusing solely on teacher training, the courses also prioritize community building by fostering communication among teachers and supporting the development of a broader STEM teacher community. Additionally, some content reflects European contexts and may require adaptation elsewhere. The official platform is hosted at https://www.scientix.eu/resources/pd-resources/moocs. Figure 4 illustrates the Scientix MOOCs interface, showcasing courses on citizen science, sustainability, and teacher professional development.

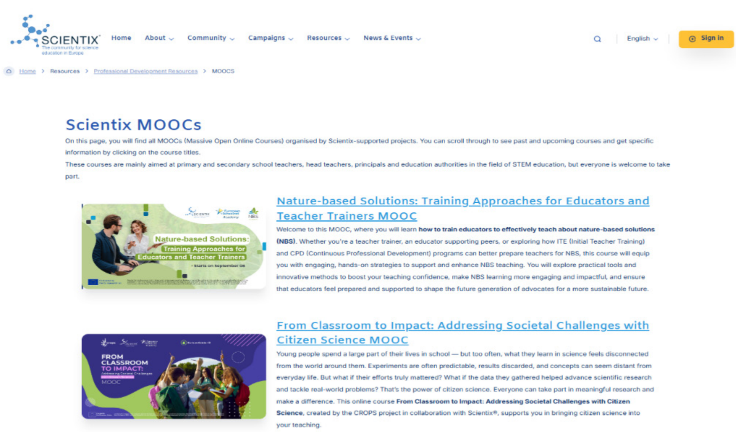

Figure 4. Scientix MOOCs Platform Interface

Supplementary Platforms

The primary platforms selected for in-depth discussion are TeachEngineering, NASA STEM Engagement, and STEM Learning and Scientix MOOCs. These platforms are distinguished by their breadth, strong institutional support, and comprehensive approach to STEM education. Nevertheless, other widely used platforms also play an important role in shaping the global landscape. These platforms are considered here as supplementary cases, as they typically focus on more specialized aspects of STEM learning rather than providing the broad curriculum integration or professional development opportunities of the main four. Nevertheless, their popularity and educational value make them important for a holistic view.

PhET Interactive Simulations

Developed by the University of Colorado Boulder, PhET offers free interactive simulations in physics, chemistry, biology, earth sciences, and mathematics. The simulations are designed to make abstract concepts more concrete by enabling students to manipulate variables and observe outcomes in real time. PhET has been widely adopted internationally and translated into multiple languages, making it highly accessible. Its main limitation is that it focuses primarily on simulations rather than providing full curriculum support, teacher professional development, or assessment tools. The platform can be accessed at https://phet.colorado.edu. Figure 5 shows the PhET Interactive Simulations platform, which provides free, inquiry-based digital tools to support science and math learning worldwide.

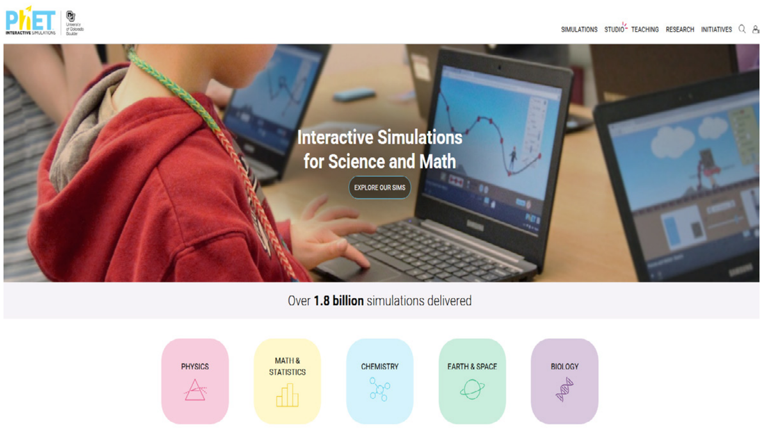

Figure 5. PhET Interactive Simulations Platform Interface

Code.org.

A nonprofit initiative, Code.org provides free resources to promote computer science education, with an emphasis on programming, computational thinking, and equity of access. Its materials are designed for K–12 students and include engaging activities such as the "Hour of Code," which introduces millions of learners worldwide to coding. While

Code.org has had a major impact on global awareness of computer science, it is somewhat narrower in scope compared to broader STEM platforms, focusing heavily on computing rather than the full STEM spectrum. The platform is available at https://code.org. Figure 6 illustrates the Code.org platform, which offers accessible computer science learning pathways for students, educators, parents, and schools.

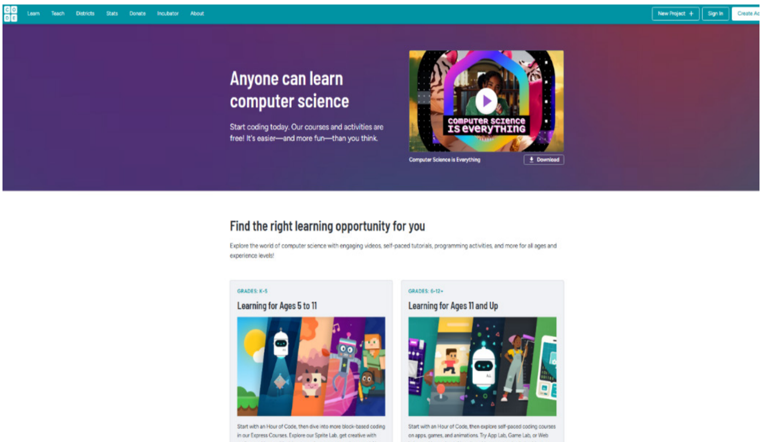

Figure 6. Code.org Platform Interface

OpenSciEd.

OpenSciEd is an open educational resource initiative that develops free, high-quality, NGSS-aligned science curriculum units for middle and high school students. Its strength lies in providing carefully structured, inquiry-based units that teachers can implement directly in classrooms. However, its resources are currently limited in subject coverage (primarily science) and require adaptation for non-U.S. curricula. While highly valuable, its narrower disciplinary and grade-level scope distinguishes it from more comprehensive platforms like STEM Learning or TeachEngineering. Further information is available at https://www.openscied.org. Figure 7 illustrates the OpenSciEd platform, which provides free, NGSS-aligned science curriculum units designed to support inquiry-based learning.

In summary, these platforms illustrate the diversity of the open-source and online STEM education ecosystem. PhET contributes powerful tools for interactive conceptual understanding, Code.org expands access to computer science, and OpenSciEd provides structured, open science units. Although they are more limited in scope compared to the primary platforms discussed earlier, their wide adoption and demonstrated impact make them essential complements to the larger ecosystem of STEM education platforms.

Figure 7. OpenSciEd Platform Interface

Overcoming STEM Teaching Barriers with Digital Platforms

Open sources and online platforms offer significant advantages in terms of accessibility, adaptability, and alignment with curricular standards. Their structured and openly accessible resources enable teachers to implement STEM activities more effectively without the need to design every component from scratch. Because of these features, such platforms hold strong potential for addressing key barriers identified in the literature. Among the most frequently reported are time and workload constraints, pedagogical and assessment challenges, limited opportunities for teacher professional development, and difficulties with curriculum integration (Estapa & Tank, 2017; Huang et al., 2022). In the following sections, selected vignettes illustrate how open-source and online STEM platforms can help mitigate these challenges through classroom-ready resources, scaffolding tools, and professional support mechanisms.

Vignette 1: Overcoming Time and Intensity Challenges with TeachEngineering

Ms. Adali, a middle school science teacher, knew that designing a full engineering challenge would take days or even weeks. Such a challenge would need to include materials, instructions, standards alignment, and assessments. With limited class hours and a packed syllabus, the task seemed daunting. One afternoon, she opened the TeachEngineering curriculum library and filtered for “Maker Challenges” and “Activities” requiring up to six hours of class time. She found a ready-made project titled "Clean Enough to Drink: Making Devices to Filter Dirty Water."

The lesson was designed for grades 3–5 and lasted six hours, divided into eight 45-minute periods. The estimated cost was about $5 per group. Teachers received extensive support materials, including background information, objectives, worksheets, rubrics, assessment suggestions, and extension ideas. Instead of designing all of these from scratch, Ms. Adali quickly adapted the activity to her class schedule and available supplies.

When she ran the activity, students enthusiastically designed, tested, and iterated their own water filtration prototypes using everyday materials such as plastic bottles, sand, and cloth. Because the heavy preparation had already been done, Ms. Adali could focus on facilitating inquiry, guiding discussion, and connecting student work to core science and engineering standards. What would once have been a multi-day planning burden became a smooth, efficient, and highly engaging engineering unit.

How TeachEngineering Helps Address Time & Workload Constraints

The TeachEngineering curriculum library demonstrates how open-source platforms can directly address the challenge of time and intensity in STEM education. Teachers can filter by grade level, activity type, time required, engineering category, and standards alignment to quickly identify activities that fit their instructional context. Because lessons are scaffolded with step-by-step procedures, detailed teacher guides, materials lists, time estimates, assessments, and extension ideas, teachers save hours of planning time.

This structure allows educators to select activities that align with their available class periods and adapt them without starting from scratch. The inclusion of low-cost, accessible materials reduces logistical barriers, while built-in standards alignment ensures curricular relevance. By providing high-quality, classroom-ready resources, TeachEngineering allows teachers to integrate hands-on STEM experiences efficiently, turning what might feel like an overwhelming preparation task into an achievable and rewarding teaching experience.

Challenges and Solutions Linked to the Vignette

The case of Ms. Adali highlights how time and workload are central barriers for teachers who want to integrate meaningful STEM activities.

While TeachEngineering reduces preparation demands through ready-to-use, scaffolded lessons, several challenges remain. Equity and accessibility can still pose obstacles. Even low-cost activities, such as the water filtration challenge, assume that teachers can obtain basic materials and have access to the internet to download resources. In under-resourced schools, these assumptions may not always hold. A possible solution is for teachers to take advantage of TeachEngineering's detailed materials lists to plan well in advance, substitute with locally available items, and share resources collaboratively with colleagues. Offline availability of PDFs also ensures that teachers can still use the resources without a constant internet connection.

Teacher readiness is another challenge. Although the lesson includes rubrics and guides, some teachers may feel uncertain about facilitating open-ended design activities. To address this, platforms like TeachEngineering recommend starting with shorter, simpler activities, gradually building confidence before attempting multi-day challenges. Pairing teachers through professional learning communities or using MOOCs such as those offered by Scientix can also strengthen support. By recognizing these challenges, teachers can overcome barriers of time and intensity. Platform features such as downloadable resources, flexible material substitutions, step-by-step scaffolds, and opportunities for collaboration also make STEM experiences more accessible and equitable for students.

Tips for Teachers: Managing Time and Workload with TeachEngineering

- Start with ready-to-use activities. Use the platform's filters (e.g., grade level, activity type, estimated time) to select projects that fit your available class hours.
- Plan materials flexibly. The detailed supply lists can be adapted using low-cost or locally available alternatives, making activities more feasible in resource-constrained settings.
- Download and save resources offline. PDFs, guides, and worksheets can be stored for later use, reducing reliance on constant internet access.
- Build confidence gradually. Begin with shorter activities to gain comfort with facilitating open-ended tasks before attempting multi-day design challenges.
- Leverage professional networks. Share adaptations and classroom experiences with colleagues or online communities (e.g., Scientix, teacher forums) to exchange strategies and reduce preparation burden.

These strategies allow teachers to enjoy the benefits of open-source platforms like TeachEngineering while addressing challenges of limited time, heavy workloads, and equity in access.

Vignette 2: Navigating Pedagogical and Assessment Challenges with Mission to the Moon

Mr. Evans, a primary science teacher, was excited about introducing STEM activities to his Year 5 students. He believed in the value of problem-based and inquiry-driven learning but often found it difficult to design activities that balanced excitement with clear learning outcomes. More importantly, he struggled with assessing not just "what" students learned but how they collaborated, generated ideas, and solved problems. Traditional quizzes or short-answer questions felt inadequate for capturing these dimensions. Traditional quizzes could measure facts, but they could not capture how students brainstormed, tested prototypes, or defended their decisions. Preparing both the activity and assessment tools often took so much time that Mr. Evans hesitated to attempt it at all. One afternoon, he discovered the Mission to the Moon resource on the STEM Learning platform. The collection provided a set of ready-mades, real-world challenges linked to space exploration—such as designing lunar landers, testing materials that could withstand extreme lunar conditions, and building simple rovers from recycled items. What immediately caught Mr. Evans's attention was the structure: each activity came with curricular links, background notes, and clearly defined student roles like astronomer, engineer, and geologist. This structure meant he could set up an inquiry-based project without having to invent everything from scratch.

He chose the activity where students had to build and test their own lunar lander models. The guidance included step-by-step instructions, suggested materials, prompts for group discussion, and learning objectives. Instead of drafting new rubrics, Mr. Evans adapted the provided outcomes into a simple checklist: Did students share ideas? Did they test and refine their designs? Could they explain why their final model worked (or didn't) using scientific reasoning? When he ran the activity, students immediately engaged with the problem. Some groups debated how to balance weight and stability, while others argued about the best materials to absorb impact. There were moments of failure—rockets that tipped over or landers that collapsed—but students quickly went back to redesigning and retesting. As he observed, Mr. Evans realized he was finally able to focus on how students collaborated and thought critically rather than spending his energy on logistics. By the end of the project, he had evidence of both content knowledge and key

STEM competencies like teamwork, creativity, and problem-solving. What once seemed like an overwhelming pedagogical and assessment challenge became a manageable and rewarding classroom experience. By the end of the unit, Mr. Evans felt more confident about integrating problem-based approaches into his teaching. The resource didn't eliminate every challenge, but it gave him a scaffold to evaluate creativity and teamwork alongside scientific understanding.

STEM Learning Helps Address Pedagogical and Assessment Challenges

The Mission to the Moon resource demonstrates how online platforms can ease the burden of implementing problem-based, project-based, and inquiry-driven learning. By offering scaffolded activities with clear objectives, background notes, group roles, and suggested assessment strategies, it reduces both planning and evaluation challenges. Teachers can shift their attention from designing every detail to facilitating and observing learning. The structured format also ensures that assessment goes beyond content recall. Students' collaboration, creativity, and critical thinking are made visible through group roles, iterative design processes, and opportunities for reflection. Teachers, in turn, can adapt provided rubrics or checklists to capture these higher-order skills more systematically.

Challenges and Solutions Linked to the Vignette

Even with strong resources such as Mission to the Moon, teachers may still encounter difficulties when implementing problem-based and inquiry-driven lessons. One common challenge is equity and participation. In group settings, certain students often dominate while others remain passive, which can undermine the collaborative intent of the activity. A practical solution is to rotate roles—such as astronomer, engineer, or geologist—so that all students experience leadership, technical, and reflective tasks. Another issue is the subjectivity of assessment. Measuring collaboration, creativity, and critical thinking can feel inconsistent, especially for teachers used to traditional tests. To address this, teachers can adapt the suggested learning outcomes included in the resource into simple observation checklists. This makes assessment more systematic and transparent while still capturing higher-order skills.

Time pressure also poses a significant obstacle. Inquiry-based projects often take longer than standard lessons, which can discourage teachers from using them. One solution is to adapt activities by focusing on the most critical stages, such as design and testing, rather than attempting to complete every step of the project. This allows teachers to preserve the spirit of inquiry within realistic time constraints. Finally, confidence in facilitation remains an important concern. Teachers without strong backgrounds in engineering or space science may feel uncertain about guiding these kinds of projects. In such cases, the background notes and teacher guides provided by Mission to the Moon can help fill knowledge gaps and provide reassurance, enabling teachers to focus on facilitation rather than content expertise.

Tips for Teachers: Managing Pedagogy and Assessment with STEM Learning

- Use structured group roles (astronomer, engineer, geologist) to make collaboration both visible and assessable.
- Adapt provided rubrics into observation checklists rather than creating assessment tools from scratch.
- Rotate responsibilities so all students practice creativity, leadership, and technical thinking.
- Break down large projects into smaller steps if time is limited.
- Ask reflective questions (e.g., *"What did your team change in your design, and why?")* to capture critical and creative thinking in real time.

Vignette 3: Feeling Behind in Digital & Pedagogical Tools

Ms. Jordan, a secondary school teacher, often felt she was falling behind. New digital tools, interdisciplinary approaches, and project-based pedagogies were being discussed at conferences and in staff meetings, but she had never received formal training on how to use them. While she was confident in teaching science content, she struggled to design lessons that connected her subject to mathematics, technology, or engineering, and she worried that her students saw STEM as too "academic" and disconnected from real life. What she needed was structured, high-quality professional development that could help her bridge these gaps without overwhelming her already busy schedule. One day she discovered STEM Is Everywhere! MOOC, a course hosted on the European Schoolnet Academy through the Scientix initiative. The course promised to guide teachers in integrating real-world problems into their STEM lessons. Its modules ranged from "Real-world problems for STEM subjects" to "Interdisciplinary STEM teaching with real-world problems," and participants were required to design and submit a real-world STEM lesson plan as a final assignment. For Ms. Jordan, this structure was transformative: she was not just reading about pedagogy, she was applying it directly to her own classroom. By the end of the course, she had designed a unit where her students investigated air quality around the school, analyzed the data, and proposed engineering solutions. In the peer-review process, she reviewed others' lesson plans and received feedback on her own. Through this exchange, she built confidence and gained insight into multiple approaches to similar challenges.

Scientix Helps Address Professional Development Gaps

STEM Is Everywhere! MOOC directly addresses one of the biggest challenges in STEM education: the lack of continuous, high-quality professional development for teachers. Rather than leaving educators to navigate new tools and approaches alone, the course provides a guided pathway with concrete resources, activities, and examples. By focusing on real-world problems, the course helps teachers link STEM to everyday contexts, making lessons both more engaging for students and more feasible for teachers to implement. Importantly, the course also builds a professional learning community. Through peer reviews, discussion forums, and social media groups like #STEMIsEverywhereMOOC, teachers can share experiences, best practices, and resources. This collaboration helps teachers stay current with evolving practices while also reducing the sense of isolation that often accompanies professional growth.

Challenges and Solutions Linked to the Vignette

Even with such structured opportunities, challenges remain. The most pressing is time: teachers already face heavy workloads, and dedicating hours to a MOOC can feel unrealistic. Breaking the course into smaller, weekly goals can make the learning process manageable. One way to do this is by completing one module at a time. Another challenge is contextual adaptation. While the course provides rich examples, they may not always align perfectly with a teacher's local curriculum or resources. Teachers like Ms. Jordan could benefit from localizing activities, such as using nearby environmental data rather than relying on European case studies. The peer-review system supports this adaptation by exposing teachers to diverse strategies and contexts. Finally, there is the issue of sustainability. A single MOOC may inspire change, but without continued support, teachers risk reverting to old practices. For this reason, Scientix encourages teachers to join broader professional networks, attend follow-up courses, and even work toward becoming Scientix ambassadors, ensuring that the professional development continues beyond one course.

Tips for Teachers: Making the Most of MOOCs for Professional Growth

- Treat MOOC modules as bite-sized learning chunks — dedicate short time slots (e.g. 1 module per week) instead of trying to complete everything at once.
- Design the required lesson plan around a real issue in your local context so the effort directly benefits your classroom.
- Engage fully in peer reviews to gain diverse perspectives and constructive feedback. Create peer learning groups (with colleagues or online MOOC participants) to discuss readings, co-plan lessons, and adapt ideas collaboratively.
- After completing a module, try one small classroom experiment (e.g. use one strategy or tool) rather than attempting an entire unit at once.
- Adapt and localize MOOC examples to match your students' realities, curriculum, and available resources.
- Archive resources and stay connected with the MOOC community to extend professional learning beyond the course itself.

Vignette 4: Facing Curriculum Integration Challenges

Mr. Rivera, a high school science teacher, was eager to design a project that connected physics principles with real-world engineering applications. However, since his background training was primarily in biology, he felt uncertain about guiding students through engineering design tasks. While searching for help, he discovered several platforms that offered structured entry points into interdisciplinary teaching. On TeachEngineering, he found ready-made lessons where engineering design was embedded within physics and environmental science contexts, including activities on renewable energy systems. These resources gave him a clear framework for integrating engineering into his science classes.

Turning to NASA STEM Engagement, Mr. Rivera used multimedia simulations and space-related challenges to highlight the role of technology in scientific discovery. This helped him bring authentic technology integration into his lessons without needing to develop resources from scratch. At the same time, STEM Learning provided him with teacher guides on interdisciplinary STEM pedagogy. Even though he wasn't trained in mathematics instruction, the platform's guidance helped him understand how to frame cross-disciplinary projects and assess student learning.

To support conceptual understanding, he used PhET simulations to demonstrate physics concepts interactively, lowering the barrier for integrating mathematic ideas. Finally, through Scientix, Mr. Rivera connected with other European educators who had already experimented with interdisciplinary projects, gaining concrete strategies for adapting resources to his local context. By combining these platforms, Mr. Rivera realized he didn't need to be an expert in every STEM discipline to design integrated lessons. Instead, he could rely on open source and online platforms to provide the scaffolding and professional guidance he lacked in his formal training.

Tips for Teachers: Overcoming Curriculum Integration Challenges

- Use structured resources (e.g., TeachEngineering lesson plans, NASA STEM engagements modules) to embed engineering and technology naturally into science or math classes.
- Start small with simulations (e.g., PhET) to introduce cross-disciplinary concepts in an accessible way before moving into larger projects.
- Seek professional development through platforms like STEM Learning, which offer CPD resources on interdisciplinary teaching.
- Join teacher communities (e.g., Scientix) to learn how others integrate multiple STEM disciplines and adapt materials across national contexts.
- Blend resources strategically. Combining different platforms can reduce the burden of designing everything alone and provide balance between content, pedagogy, and practical implementation.

These approaches ensure that teachers with expertise in one discipline can still design meaningful interdisciplinary STEM experiences by leveraging the strengths of multiple platforms.

Taken together, open-source and online platforms are enriching STEM education by extending accessibility, fostering collaboration, and supporting interdisciplinary problem-solving (Navas-Bonilla et al., 2025; Sanabria-Z. et al., 2024). Their capacity to align with curricula, provide adaptable resources, and offer professional development enables teachers to address barriers such as curriculum integration, assessment, and workload (Estapa & Tank, 2017; Huang et al., 2022). At the same time, the broader evolution of openness in education—from OER initiatives to MOOCs—has reinforced the pedagogical value of adaptability, equity, and democratization of knowledge (Mishra, 2017; Sousa et al., 2023). While challenges of contextual adaptation and teacher readiness remain, the platforms examined here illustrate how digital ecosystems can transform STEM instruction into a more inclusive, efficient, and globally relevant practice (Chu, 2025; Dao et al., 2025).

References

Awad, N. (2023). Exploring STEM integration: Assessing the effectiveness of an interdisciplinary informal program in fostering students' performance and inspiration. *Research in Science & Technological Education, 41*(2), 675–699. https://doi.org/10.1080/02635143.2021.1931832

Chu, Y. (2025). Revolutionizing STEM education through emerging technologies. *American Journal of STEM Education: Issues and Perspectives, 10*, 71–80. https://doi.org/10.32674/bkw4ty40

Couso, D., & Simmaro, C. (2020). STEM education through the epistemological lens: Unveiling the challenge of STEM transdisciplinarity. In C. C. Johnson, M. J. Mohr-Schroeder, & T. J. Moore (Eds.), *Handbook of research in STEM education* (pp. 17–28). Routledge.

Dao, V.-P., Nguyen, T.-L., Bui, V.-H., & Nguyen, M.-D. (2025). Developing a digital platform ecosystem for distance learning and STEM education. *Journal of Information Systems Engineering and Management, 10*(38), 218–226. https://doi.org/10.52783/jisem.v10i38s.6842

English, L. D., King, D., & Smeed, J. (2017). Advancing integrated STEM learning through engineering design: Sixth-grade students' design and construction of earthquake resistant buildings. *The Journal of Educational Research, 110*(3), 255–271. https://doi.org/10.1080/00220671.2016.1264053

Estapa, A. T., & Tank, K. M. (2017). Supporting integrated STEM in the elementary classroom: A professional development approach centered on an engineering design challenge. *International Journal of STEM Education, 4*(6). https://doi.org/10.1186/s40594-017-0058-3

Huang, B., Jong, M. S.-Y., Tu, Y.-F., Hwang, G.-J., Chai, C. S., & Jiang, M. Y.-C. (2022). Trends and exemplary practices of STEM teacher professional development programs in K-12 contexts: A systematic review of empirical studies. *Computers & Education, 189*, 104577. https://doi.org/10.1016/j.compedu.2022.104577

Josué, A., Bedoya-Flores, M. C., Mosquera-Quiñonez, E. F., Mesías-Simisterra, Á. E., & Bautista-Sánchez, J. V. (2023). Educational platforms: Digital tools for the teaching-learning process in education. Ibero-American J*ournal of Education & Society Research, 3*(1), 259–263. https://doi.org/10.56183/iberoeds.v3i1.626

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education*. International Journal of STEM Education, 3*(1), 1–11. https://doi.org/10.1186/s40594-016-0046-z

Li, K. C., & Wong, B. T. M. (2021). A review of the use of open educational resources: The benefits, challenges and good practices in higher education. *International Journal of Innovation and Learning, 30*(3), 279–298. https://doi.org/10.1504/IJIL.2021.118599

Liu, M., & Yu, D. (2023). Towards intelligent e-learning systems. *Education and Information Technologies, 28*, 7845–7876. https://doi.org/10.1007/s10639-022-11479-6

Mexhuani, B. (2025). Adopting digital tools in higher education: Opportunities, challenges and theoretical insights. *European Journal of Education, 60*(1), Article e12819. https://doi.org/10.1111/ejed.12819

Mishra, S. (2017). Open educational resources: Removing barriers from within. *Distance Education, 38*(3), 369–380. https://doi.org/10.1080/01587919.2017.1369350

Navas-Bonilla, C., Guerra-Arango, J. A., Oviedo-Guado, D. A., & Murillo-Noriega, D. E. (2025). Inclusive education through technology: A systematic review of types, tools and characteristics. *Frontiers in Education*, *10*. https://doi.org/10.3389/feduc.2025.1527851

Oussous, A., Menyani, I., Srifi, M., Lahcen, A. A., Kheraz, S., & Benjelloun, F.-Z. (2023). An evaluation of open source adaptive learning solutions. *Information, 14*(2), Article 57. https://doi.org/10.3390/info14020057

Sanabria-Z., J., Alfaro-Ponce, B., González-Pérez, L. I., & Ramírez-Montoya, M. S. (2024). Reusable educational resources for developing complex thinking on open platforms. *Education and Information Technologies, 29*, 1173–1199. https://doi.org/10.1007/s10639-023-12316-0

Sousa, L., Pedro, L., & Santos, C. (2023). A systematic review of systematic reviews on open educational resources: An analysis of the legal and technical openness. *International Review of Research in Open and Distributed Learning, 24*(3), 18–33. https://doi.org/10.19173/irrodl.v24i3.7196

Stracke, C. M., Downes, S., Conole, G., Burgos, D., & Nascimbeni, F. (2019). Are MOOCs Open Educational Resources? A literature review on history, definitions and typologies of OER and MOOCs. *Open Praxis, 11*(4), 331–341. https://doi.org/10.5944/openpraxis.11.4.1010

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Chapter 8

STEM and Arts Integration: STEAM Approach

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Chapter Highlights

The following points outline the fundamental dimensions of the STEAM approach, highlighting its conceptual scope, educational significance, and practical implications for teaching and learning. Together, these points emphasize how STEAM supports interdisciplinary integration, enriches instructional practices, and contributes to the development of creativity, critical thinking, and collaboration among learners across diverse educational contexts.

- Definition and Scope – Elaborates on the conceptual foundations of the STEAM approach, clarifying its scope, key characteristics, and its distinction from traditional STEM education by emphasising the integration of artistic and creative dimensions.
- Importance of STEAM in Contemporary Education – Examines the educational significance of STEAM in modern learning environments, highlighting its role in addressing complex, real-world problems and supporting interdisciplinary and innovative thinking.
- Integration of Arts into STEM Disciplines – Discusses how the systematic incorporation of the arts into science, technology, engineering, and mathematics enhances the learning process by promoting creativity, aesthetic awareness, and deeper conceptual understanding.
- Activity and Curriculum Design – Presents illustrative examples of STEAM-based projects and learning activities designed for diverse educational contexts and age groups, demonstrating how interdisciplinary learning objectives can be effectively operationalised in classroom practice.

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Introduction

Albert Einstein's statement, *"Imagination is more important than knowledge; for knowledge is limited, whereas imagination embraces the entire world"* (Viereck, 1929), serves as a powerful reminder that education should not be confined merely to the transmission of knowledge but should also constitute a creative process that nurtures imagination. While knowledge may restrict individuals within certain boundaries, imagination transcends these limits, paving the way for new ideas, original solutions, and innovative discoveries. This perspective underlies the growing emphasis on interdisciplinary approaches in contemporary educational settings. In this context, the inclusion of the arts within STEM fields, giving rise to the STEAM approach, offers a holistic learning experience aimed at fostering both the analytical and the creative dimensions of students' development.

The concept of STEAM (Science, Technology, Engineering, Art, and Mathematics) was first introduced as an acronym in a 2009 report published by the Florida Alliance for Arts Education. Encompassing the disciplines of science, technology, engineering, the arts, and mathematics, this approach is regarded as one of the leading instructional models in contemporary education. Drawing attention with its emphasis on experiential and hands-on learning, STEAM not only aims to provide individuals with knowledge but also seeks to establish a meaningful connection between school, professional life, and society through an interdisciplinary instructional perspective (Tsupros, Kohler, & Hallinen, 2009; Allina, 2018). Çepni (2017) defines the STEAM approach as an inclusive teaching and learning model that integrates multiple fields under one framework, diverging from traditional methods by addressing disciplines in a holistic and interconnected manner. According to Dugger (2010), STEAM approach avoids presenting disciplines as fragmented and independent courses; instead, it treats them as interwoven—much like in real life—thus enabling students to perceive the world as a coherent whole rather than in isolated parts. Similarly, Çorlu et al. (2014) describe STEAM approach as a process in which teachers and students collaboratively construct knowledge, skills, and ideas through interdisciplinary cooperation that spans multiple domains.

Yakman (2008), who first articulated the theoretical foundation of the STEAM approach, defines STEAM approach in two distinct ways. First, STEAM is viewed as an approach that, while adhering to the standards of science, technology, engineering, and mathematics, also transcends these domains to encompass additional disciplines. Second, STEAM is conceptualized as a comprehensive educational model that purposefully integrates contemporary fields and instructional content in alignment with the demands of the modern era (Park & Ko, 2012). To render this abstract framework more comprehensible, Yakman employed a visual representation provided in Figure 1 of her study.

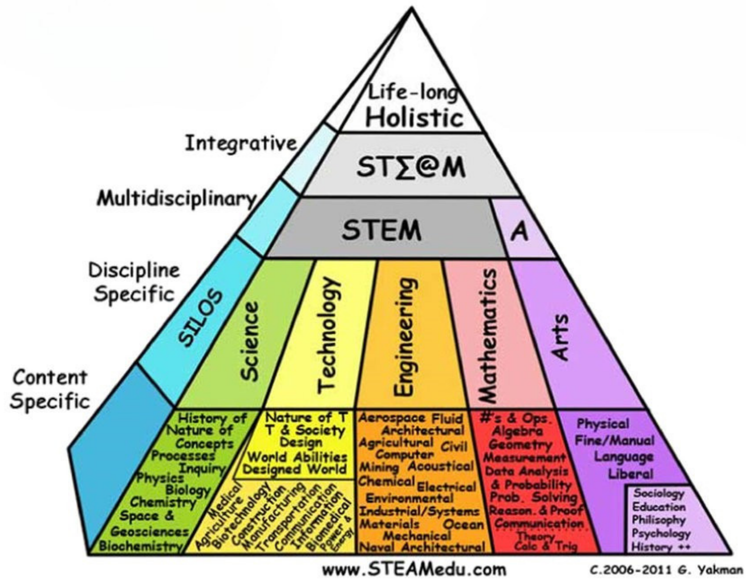

Figure 1. The STEAM Pyramid (Yakman, 2008)

The STEAM pyramid developed by Yakman represents an original model that addresses the disciplines of science, technology, engineering, arts, and mathematics within a holistic instructional framework. In this pyramid, each discipline is represented through its own body of knowledge and methodologies, while the processes of interdisciplinarity and integration are systematically constructed. Mathematics is not regarded merely as an independent field but is positioned at the center of the pyramid as the structural foundation of the other disciplines.

At the lower levels of the pyramid, discipline-specific content and methodologies are presented. The natural sciences encompass fields such as physics, chemistry, biology, and earth sciences, while technology incorporates contemporary dimensions such as informatics, communication, production, and digital media. Engineering represents applied sciences including civil, mechanical, environmental, and computer engineering. Mathematics, beyond numbers and operations, covers processes such as data analysis, probability, proof, and reasoning. The arts are not limited solely to fine arts but also include language, literature, social sciences, philosophy, and psychology, thereby strengthening the aesthetic and cultural dimensions of the interdisciplinary approach. At the intermediate levels of the pyramid, interdisciplinary collaboration takes place. At the multidisciplinary level, different subjects are conducted in parallel around a common theme—for instance, the theme of energy or the environment may be explored across multiple disciplines. However, at this stage, disciplines operate side by side without true integration. At the integrative level, disciplines converge around a shared problem or project, working together within a unified process. In this context, the arts contribute through aesthetic, ethical, and communicative dimensions, while science and engineering focus on producing solutions, and mathematics provides the systematic and analytical foundation of the process. The top level of the pyramid, referred to as the holistic level, represents lifelong learning. The purpose of this stage is to ensure that individuals transfer the knowledge acquired at school not only for academic achievement but also to daily life, professional practice, and civic responsibility. Yakman's model emphasizes that interdisciplinary knowledge integration should generate tangible and meaningful outcomes not only within educational contexts but also at both individual and societal levels. In this respect, Yakman further advanced the STEAM approach by redefining it as ST∑@M. This revised framework has been expressed as *"science and technology shaped through the language of mathematics, and manifested as the product of engineering and the arts"* (Boran-Şenocak, 2024). This definition positions mathematics as the foundational language integrating other disciplines, highlights the productive nature of engineering and the arts, and identifies science and technology as the visible outcomes of this creative process.

In the literature, it is noted that the STEAM pyramid has been associated with different educational levels. Accordingly, the discipline-specific content represented at the first level of the pyramid is considered more suitable for high school and vocational education. The second level, which represents the multidisciplinary approach, is regarded as more appropriate for middle school, whereas the third level, characterized by an integrative approach, is considered particularly suitable for both elementary and middle school education (Park & Ko, 2012; Oh, Lee, & Kim, 2013). In this framework, the association of the STEAM pyramid with various stages of education suggests that the degree of interdisciplinary integration may vary depending on learners' age and developmental characteristics. At this point, the inclusion of the arts is especially significant, as it not only strengthens interdisciplinary integration but also adds a new dimension to the learning experience.

The Importance of STEAM in Modern Education

The integration of the arts into the instructional process constitutes a significant dimension of the STEAM approach. According to Crawford (2004), the arts make learning content more comprehensible for students and transform learning into a joyful and engaging process. Furthermore, the arts enable students to establish personal connections with the subject matter and express themselves, while also facilitating the concretization of abstract concepts. In addition, the arts support the development of higher-order cognitive processes, foster a sense of community within the classroom, and strengthen students' collaborative skills. Art plays a fundamental role in enabling individuals to adapt to the society and social environment in which they live; accordingly, its position within the educational system carries equally critical significance (Kızılırmak, 2018). In this regard, the role of the arts in STEAM is not confined to providing an aesthetic contribution; rather, it offers a holistic perspective to the learning process. The arts may be seen as enabling students to interpret scientific and technological knowledge in creative ways, thereby rendering learning processes more meaningful and student-centered. Thus, the integration of the arts into STEAM is not limited to aesthetic and creative contributions but also serves to foster the cognitive and social competencies required in contemporary society. This demonstrates the strong connection between the STEAM approach and the development of 21st-century skills.

The significance of STEAM approach in the context of 21st-century skills has become increasingly evident amid the rapidly transforming social, economic, and technological conditions of today's world. As O'Neal, Gibson, and Cotten (2017) emphasize, 21st-century skills constitute essential competencies that enable individuals to meet their needs in a technology-driven society and to attain a competitive position on a global scale. In this regard, the framework developed by the Partnership for 21st Century Skills (2018) systematically categorizes these competencies under three domains. The first domain, learning and innovation skills, encompasses cognitive and social dimensions such as creative thinking, critical thinking, problem solving, communication, and collaboration. The second domain, information, media, and technology skills, aims to foster individuals' proficiency in information literacy, media literacy, and ICT literacy. Finally, the third domain, life and career skills, includes flexibility and adaptability, self-direction, social skills, productivity, accountability, and leadership—competencies that allow individuals to effectively adapt to changing life circumstances. This holistic structure provides a foundation for equipping individuals with the knowledge, skills, and attitudes required to meet the demands of the contemporary era.

At this point, the core objectives of STEAM approach directly align with the aforementioned framework. As Ergen and Güler (2023) state, the STEAM approach does not merely aim to transmit academic knowledge but also seeks to cultivate individuals who are inquisitive, capable of critical perspectives, able to think divergently, develop entrepreneurial skills, and address problems through technology-supported solutions. In line with this aim, students are encouraged to enhance their creative thinking, problem-solving, collaboration, and innovative production skills. Each discipline within STEAM contributes to this development from different perspectives: science and mathematics strengthen analytical thinking; engineering emphasizes problem-solving and design-oriented thinking; while the arts foster creativity and aesthetic sensitivity. The integration of these disciplines enables students not only to acquire knowledge at an abstract level but also to relate it to real-world problems. This interdisciplinary approach encompasses not only individual development but also a broader dimension that supports societal progress. As Nacaroğlu and Kızkapan (2021) emphasize, individuals equipped with skills gained through STEAM approach make significant contributions to the economic and social life of nations. The development of innovative products and services supports economic growth, while such individuals also play an active role in addressing societal challenges. Consequently, STEAM approach serves as a bridge that connects individual creativity with societal well-being and is regarded as an important instrument in achieving sustainable development goals.

The Integration of the Arts into STEM

Since the earliest periods of human history, art has been one of the primary means through which individuals express themselves, while also playing a central role in the cultural and social development of societies. Read's (1966) assertion that *"Art is a mechanism in life, and without it, societies lose their balance"* clearly illustrates that art is not merely a personal pursuit but also a crucial element in sustaining social balance and sustainability. From this perspective, education systems should regard art not as a secondary activity but as a fundamental domain of learning. This is because cultivating individuals who can adapt to contemporary conditions, think critically, act innovatively, and demonstrate creativity is directly linked to the integration of arts education into learning processes from the earliest stages of schooling. Research demonstrates that children's engagement with art enhances their emotional intelligence, strengthens their problem-solving abilities, and supports their social interactions (Çimen et al., 2025). Moreover, art increases individuals' self-confidence, enabling them to express themselves more freely and to recognize their personal differences.

The role of art in education is not confined to childhood. Sousa and Pilecki (2018) emphasize that art contributes to human holistic development by activating cognitive, emotional, and psychomotor pathways. This holistic perspective reveals that learning is not merely the acquisition of knowledge but also a process that incorporates emotions, values, and creativity. For this reason, educational institutions bear a critical responsibility to introduce art to children at an early age and to position it not as an optional activity but as a core component of the curriculum. In doing so, students' learning experiences are enriched, knowledge retention is strengthened, and lifelong learning processes become more meaningful and effective. At this point, the rise of the STEM approach is particularly noteworthy. Bringing together the disciplines of science, technology, engineering, and mathematics, the STEM model has been placed at the center of the educational policies of many countries in recent years. STEM education aims to enhance technological production capacity, contribute to economic growth, diversify employment opportunities, and cultivate individuals with strong global competitiveness (Honey et al., 2014; Çepni, 2018). However, the cognitive foundation provided by STEM alone may not be sufficient to foster the higher-order skills demanded by contemporary society, such as creativity, innovation, and critical thinking. Indeed, Ulus (2024) argues that the four-discipline structure of STEM contributes primarily to equipping individuals with technical knowledge but tends to overlook aspects such as individual creativity and aesthetic sensitivity. Such critiques underscore the necessity for a more inclusive and holistic approach to education. As a natural response to this need, the STEAM approach emerged, proposing the integration of the arts into STEM. Yakman's (2008) STEM+A framework does not confine interdisciplinary interaction to numerically based fields but also incorporates the arts, thereby embedding aesthetic sensitivity, creativity, and innovative problem-solving skills into the educational process. STEAM enables students to gain a multidimensional learning experience through both analytical thinking and artistic production. In this way, individuals are equipped not only with academic competencies but also with the ability to develop sensitivity to social issues, integrate diverse perspectives, and generate creative solutions.

Research on the integration of the arts into STEM clearly demonstrates the positive effects of this approach on students. Çimen et al. (2025) and Mercin (2019) report that STEM practices enriched with the arts increase students' motivation toward learning, enhance their problem-solving skills, and foster more active participation in learning processes. These findings indicate that the transition from STEM to STEAM is not merely a conceptual expansion but rather the construction of a holistic educational paradigm responsive to the demands of the contemporary era. As Mercin (2019) emphasizes, imagination-driven, creative, and aesthetic thinking skills cultivated through the arts contribute to individuals becoming better mathematicians, engineers, and scientists. Thus, the arts are regarded as a complementary element that balances the abstract and technical aspects of STEM, enriching them with emotional and aesthetic perspectives.

A critical issue for the effective implementation of STEAM approach is the identification of the key elements that should be taken into account in program design. In this regard, Park and Ko (2012) refer to seven stages that need to be considered in shaping the content structure of STEAM approach.

1. **Connection, Integration, and Coherence:** For STEAM approach to be implemented effectively, it is essential that it be applied in a manner that does not conflict with the existing curriculum. In this context, systematic connections need to be established with core areas such as science, technology, and engineering. Moreover, integrative thinking activities may be organized both in relation to each discipline individually and through collaborative, cross-disciplinary engagement.
2. **Fostering Diversity and Creative STEAM Practices:** In order for students to develop diverse perspectives, they require learning experiences that enable them to understand how fundamental scientific principles can be adapted to various technologies and applied to real-life contexts through engineering. Therefore, instructional activities supported by interdisciplinary connections constitute the essential conditions of STEAM approach, which aims to nurture creative thinking.
3. **Teacher Competence for Effective and Innovative Instruction:** Strengthening the creative dimension of STEAM approach is possible only when teachers have access to diverse and innovative instructional methods, learning tools, and experimental practices. However, although the concept of the "creative experiment" is frequently invoked today, such experiments can be genuinely creative only if they are developed in alignment with the fundamental

principles of STEAM.

4. **Cultivating a Holistic Perspective:** One of the primary objectives of STEAM approach is to foster a perspective that emphasizes comprehension of the whole rather than focusing solely on details. In other words, it is essential that students develop the ability to perceive not only the individual parts but also the larger picture that those parts collectively form.
5. **Relevance in the Face of Rapidly Changing Technology:** In today's world, where knowledge and technology are in constant transformation, the scientific and technological foundations of the past can quickly become obsolete. Therefore, it is essential that STEAM approach maintain sufficient flexibility to adapt to emerging technologies and adopt a "just-in-time learning" approach.
6. **Foresight and Realistic Applications for the Future:** While STEAM approach is structured around science, technology, and engineering, it should also be connected to politics, society, environment, economy, and ethical values. In this way, students can develop a practical and realistic perspective grounded in integrated thinking and creativity, enabling them to anticipate the future.
7. **Integrated Design Approach in Engineering:** The integrated design approach within the field of engineering can be regarded as one of the fundamental dynamics of STEAM approach. Supported by group work, this approach not only equips students with experimental competencies in science, technology, and engineering but also provides opportunities to develop ethical awareness, social responsibility, leadership, communication, and collaboration skills. In this way, education fosters not only qualified scientists, engineers, and technology experts but also the future decision-makers, policymakers, and social leaders.

Examples of STEAM Activities for Various Educational Contexts

The holistic perspective that the STEAM approach brings to education is not limited to the theoretical level but is concretized through practical activities designed for different age groups. One of the strongest aspects of interdisciplinary learning is its capacity to create creative learning environments that address students' individual interests and abilities (Balım & Yürümezoğlu, 2023). Within this framework, the integrated treatment of science, technology, engineering, arts, and mathematics enables students to develop both analytical and creative problem-solving skills.

Particularly, STEAM activities designed for different age groups strengthen the universal principle of "student-centeredness" in education. In early childhood, simple art-based engineering experiments support children's imagination and motor skills, whereas at the middle and high school levels, interdisciplinary projects foster complex problem-solving, innovative thinking, and collaboration skills (İnce & Mısır, 2018; Vurucu-Şahin & Şahin, 2020; Madenci & Yılmaz, 2019). In this context, the diversity of activities that can be implemented across various stages of the curriculum demonstrates that STEAM contributes not only to academic achievement but also to individual development and social engagement.

Indeed, the project examples published on the platform *www.sciencebuddies.org* and developed for different age groups clearly demonstrate the practical potential of the STEAM approach. These projects do not confine learning processes to the mere transmission of knowledge but instead support them through experiential, production-oriented, and creative applications. In this way, students are provided with opportunities to relate scientific knowledge to everyday life, use technological tools effectively, develop engineering designs, reinforce mathematical thinking in applied contexts, and express their artistic sensitivity. Below are selected visuals from STEAM projects designed for different age groups. In this way, it is emphasized that STEAM is not merely a theoretical model but also a dynamic educational approach enriched through concrete experiences.

Figure 2. Mini Earthquake Table (URL-1)

Mini Earthquake Table: The aim of this project is to enable students to investigate the effects of earthquakes through experiential learning. A simple earthquake table is constructed, upon which LEGO® structures of varying heights are built, and the resilience of these structures against tremors is observed. Measurements supported by smartphone sensors provide students with the opportunity to experience both the experimental and technological dimensions of science simultaneously. In addition to facilitating the applied learning of engineering principles, this activity stands out as an educational practice that fosters creativity and interdisciplinary thinking.

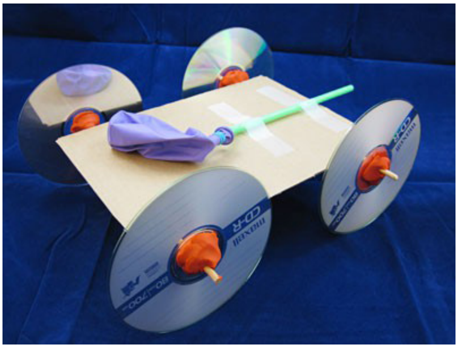

Figure 3. Balloon-Powered Vehicle (URL-2)

Balloon-Powered Vehicle: The aim of this project is to design a vehicle that can travel the farthest and fastest using only the potential energy stored in a balloon. Constructed from simple materials, the vehicle consists of a body, wheels, and axles connecting the wheels to the body. When the balloon is inflated, the air pressure inside and the stretched rubber surface store energy; once released, this potential energy is converted into kinetic energy as the air rapidly escapes. In accordance with Newton's third law of motion *"for every action, there is an equal and opposite reaction"* the backward release of air propels the vehicle forward. Through this simple apparatus, students are able to observe energy transformations, laws of motion, and the engineering design process, thereby enhancing both their scientific understanding and their creativity.

Tower Design: This STEAM project allows students to experience engineering principles through the use of limited materials. The aim of the project is to construct the tallest possible tower using only paper and tape, while ensuring that the tower is strong enough to support a heavy load placed at its top. Within this context, students have the opportunity to observe, in a hands-on manner, the effects of compression and tension on structural elements, the durability of truss and frame systems, and the ways in which material shaping (e.g., rolling or folding paper) can enhance structural strength.

Figure 4. Tower Design (URL-3)

Balance in the Air: The aim of this project is to investigate whether the distance traveled by a paper airplane changes when the drag force acting upon it is increased. During flight, a paper airplane is subject to four fundamental forces: thrust, lift, weight, and drag. Thrust propels the airplane forward, while lift is generated by the airflow over the wings. Conversely, weight pulls the airplane downward due to gravity, and drag slows it down as a result of air resistance. In this project, students design a standard paper airplane and then introduce small structural modifications to increase drag, examining the differences in flight distance. In doing so, they gain the opportunity to observe experientially the effects of aerodynamic forces on flight, thereby both deepening their understanding of physics and practicing the processes of scientific inquiry.

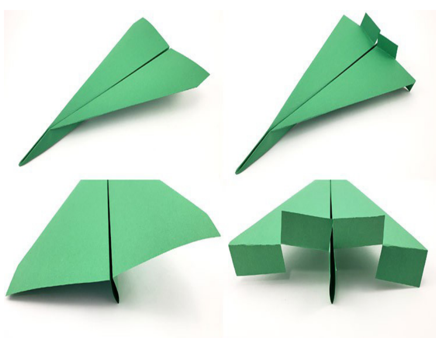

Figure 5. Balance in the Air (URL-4)

Bird Observation Box: This STEAM project aims to help students recognize the biodiversity in their immediate surroundings and to develop their scientific observation skills. The main objective of the project is to design a bird feeder using recyclable materials and, through this feeder, observe the bird species present in the local area. Birds devote much of their time to meeting their basic needs such as food, water, and shelter; therefore, a properly placed feeder provides an opportunity to study them closely without harming their natural habitats. In this process, students record the appearances, behaviors, and feeding habits of different species, thereby experiencing the fundamental research methods of ornithology. As a result, the project fosters both ecological awareness and sustainable environmental consciousness, while simultaneously teaching scientific inquiry and observation processes as a practical and creative endeavor.

Figure 6. Bird Observation Box (URL-5)

Cell Phone Stand Design: This STEAM project aims to make visible the engineering design process underlying everyday objects that are frequently used. Although a cell phone stand may appear quite simple at first glance, it actually incorporates numerous design criteria such as functionality, durability, ergonomics, and aesthetics. In this project, students engage in the process of developing their own prototypes using a variety of materials. During this process, they are encouraged to think from an engineering perspective by considering questions such as the purpose of the stand, its compatibility with different brands and sizes of phones, accessibility to functional details such as charging ports, and the structural stability of the design. Thus, this activity not only results in the creation of a practical product but also provides an interdisciplinary learning experience that fosters design-oriented thinking, problem-solving skills, and creativity.

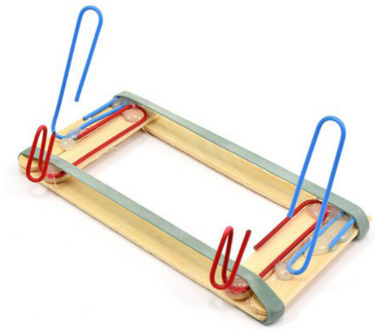

Figure 7. Cell Phone Stand Design (URL-6)

Launch and Catch: This STEAM project is a creative engineering activity in which students design a launching device capable of propelling a ball the farthest possible distance, along with a receiving mechanism to catch it, using simple materials. The project allows for the exploration of mechanical principles ranging from the operation of simple machines such as levers to more complex systems like catapults or slingshots. Students investigate concepts such as initial velocity, launch angle, and trajectory through experiential learning, thereby deepening their understanding of motion physics. They also observe the transformation of different forms of energy -such as the elastic potential energy of rubber bands or gravitational potential energy- into kinetic energy. A key component of the process is the engineering design cycle: students develop alternative designs and refine their prototypes through trial and error, mirroring the practices of real engineers. Thus, the activity provides an interdisciplinary learning experience that not only enhances physical understanding but also cultivates problem-solving, creativity, and design-oriented thinking skills.

Figure 8. Launch and Catch (URL-7)

Obstacle-Detecting Smart Glasses: This STEAM project represents an innovative engineering application aimed at facilitating the daily lives of visually impaired individuals. The objective of the project is to design and construct glasses equipped with an ultrasonic distance sensor and a buzzer to detect obstacles. The collected data are transmitted to the user through auditory alerts, providing real-time feedback about potential hazards in the environment. Going beyond the function of traditional white canes, this design offers hands-free usability, thereby enhancing comfort and safety in everyday mobility. Throughout the process, students not only assemble the electronic hardware but also learn coding, thereby experiencing all stages of the engineering design cycle. As such, the project fosters the development of socially beneficial technology while promoting interdisciplinary problem-solving and creativity as part of the learning experience.

Figure 9. Obstacle-Detecting Smart Glasses (URL-8)

Smart Plant Watering System: This STEAM project focuses on the design of an intelligent irrigation system that automatically meets the watering needs of plants. Throughout history, irrigation methods have generally relied on manual practices, whereas in modern times more efficient solutions have been developed through electronic sensors and automation systems. In this project, students build and operate an automatic watering circuit for potted plants using a soil moisture sensor, an Arduino® microcontroller, and a small pump. The system measures soil moisture levels and activates or stops the pump based on predetermined threshold values. The process requires accurate calibration of the sensors and adjustment of the water supply according to the plant's needs. In this way, students develop a sustainable solution capable of enhancing agricultural efficiency by applying skills in electronic circuit design and programming, while simultaneously gaining an interdisciplinary learning experience that integrates engineering, technology, and environmental awareness.

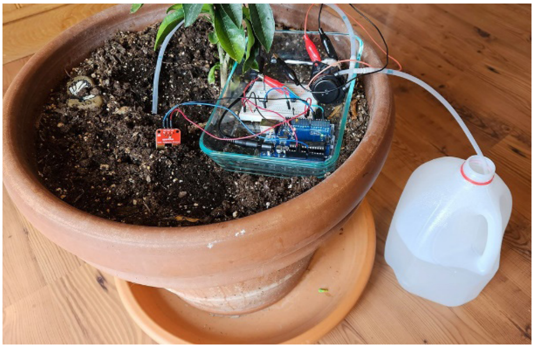

Figure 10. Smart Plant Watering System (URL-9)

Student Outcomes: Creativity, Critical Thinking, and Collaboration

As noted in the previous sections, one of the most significant contributions of STEAM approach is its multidimensional development of students' cognitive, affective, and social skills. Through its interdisciplinary structure, STEAM not only enhances individuals' academic achievement but also strengthens essential 21st-century competencies such as creativity, critical thinking, and collaboration. In this regard, studies in the literature demonstrate that STEAM practices have multifaceted and meaningful effects on students.

One of the core competencies fostered by the STEAM approach is creative thinking. Creativity is defined as the ability of an individual to construct new mental structures by drawing on observation, knowledge, experience, and thought, and to generate original concepts and innovative ideas in this process (Dikici, 2001). A creative individual is characterized as curious, capable of producing innovations, patient, open to exploration, able to use imagination effectively, and skilled in thinking through images. Moreover, such individuals stand out for their willingness to engage in experimentation and research, their capacity to synthesize data, and their ability to reach holistic judgments (Yeşilyurt, 2020). The interdisciplinary nature of STEAM enables students to develop their creativity in multiple dimensions. Indeed, a study conducted with gifted students revealed that STEAM activities promoted balanced development across artistic, scientific, and everyday forms of creativity, particularly strengthening associative and analogical thinking as well as mental flexibility (Gomez & Ros, 2024). Similarly, a study on early childhood education demonstrated that eco-print and project-based STEAM practices significantly enhanced children's creative thinking skills, supported artistic creativity, and enriched the preschool curriculum through interdisciplinary integration (Jazariyah, Athifah, Purnamasari, & Lita, 2023).

Research conducted at the primary and secondary levels likewise indicates that STEAM activities contribute to the development of scientific creativity (Karatepe, 2023; Gülhan & Şahin, 2018; Yıldırım, 2023).

Another significant outcome of STEAM approach is the development of critical thinking skills. Critical thinking is defined as a conscious and controlled mental process in which individuals question prejudices and assumptions, systematically examine and evaluate the information presented to them, and engage in reasoning. Within this process, ideas are considered from multiple perspectives, their meanings and implications are discussed, and judgments, theories, or actions are derived through methods such as analysis, logic, comparison, and inference (Gürkaynak et al., 2008). This competency is essential not only for enabling individuals to make independent, original, and autonomous decisions that lead to effective solutions in their lives but also for cultivating sensitive, responsible, participatory, and conciliatory citizens in democratic societies (Gürkaynak et al., 2008). In this respect, STEAM directly supports the development of students' critical thinking skills by centering on problem-based learning and design processes. Its interdisciplinary structure allows students to conduct multidimensional analyses, develop evidence-based reasoning, and generate alternative solutions. Indeed, a study conducted at the middle school level demonstrated that STEAM activities significantly improved students' dispositions toward critical thinking (Açışlı-Çelik, 2022). Similarly, research with seventh-grade students revealed that STEAM activities contributed positively not only to academic achievement but also to scientific creativity and science motivation, both of which are closely associated with critical thinking (Yıldırım, 2023). These findings clearly indicate that STEAM constitutes a powerful educational model that transcends traditional knowledge transmission, fostering students as inquisitive, multidimensional thinkers and solution-oriented individuals.

Another prominent outcome of STEAM approach is the development of collaboration skills. The multifaceted benefits of collaborative learning for students have been extensively documented in the literature. Laal and Ghodsi (2012) categorize these benefits into four dimensions: social, psychological, academic, and evaluative. From a social perspective, collaborative learning creates a strong support network for students, fosters understanding of diversity, establishes a positive classroom climate, and promotes the formation of learning communities. Psychologically, student-centered instructional processes enhance individuals' self-esteem, reduce anxiety, and contribute to the development of positive attitudes toward teachers. Academically, collaborative learning encourages critical thinking, increases active participation in the learning process, raises achievement levels, and allows appropriate modeling of problem-solving strategies. From an evaluative standpoint, it personalizes learning processes and provides alternative methods of student–teacher interaction. In this context, STEAM, as an interdisciplinary approach, offers a strong foundation for the development of collaboration skills. STEAM activities encourage students to take active roles in group work, to integrate diverse interests and abilities toward a common goal, and to develop a sense of responsibility. Research has shown that STEAM practices strengthen students' collaborative skills, particularly by supporting the development of social competencies such as communication, role-sharing, and leadership (Aris & Orcos, 2019; Madenci & Yılmaz, 2019). Moreover, students' ability to produce interdisciplinary outcomes through joint efforts generates a synergy that extends beyond individual learning, thereby enhancing both their cognitive and social gains.

In conclusion, the STEAM approach constitutes a powerful educational model that multidimensionally supports students' cognitive, affective, and social development. Research on creativity, critical thinking, and collaboration demonstrates that its interdisciplinary nature not only enhances individuals' academic achievement but also strengthens essential 21st-century skills such as problem-solving, innovative thinking, and democratic participation. The integration of the aesthetic, ethical, and communicative dimensions of the arts with the systematic structure of science, technology, engineering, and mathematics enables students to experience learning as more meaningful, productive, and participatory. In this regard, STEAM emerges as a contemporary and holistic educational model that goes beyond traditional knowledge transmission, fostering students as inquisitive, creative, and collaborative individuals.

References

Açışlı-Çelik, S. (2022). STEM etkinliklerinin ortaokul 6. sınıf öğrencilerinin problem çözme becerilerine, eleştirel düşünmelerine ve STEM'e yönelik tutumlarına etkisinin araştırılması (An investigation on the effect of stem practices on sixth-grade students' problem-solving skills, critical thinking, and attitudes toward STEM). *The Journal of Pamukkale University Faculty of Education*, 57, 1–27. https://doi.org/10.9779/pauefd.1054678

Allina, B. (2018). The development of STEAM educational policy to promote student creativity and social empowerment. *Arts Education Policy Review, 119*(2), 77-87. https://doi.org/10.1080/10632913.2017.1296392

Arís, N., & Orcos, L. (2019). Educational robotics in the stage of secondary education: Empirical study on motivation and STEM skills. *Education Sciences*, *9*(2), 73. https://doi.org/10.3390/educsci9020073

Balım, S., & Yürümezoğlu, K. (2023). STEAM bütünleşik öğrenme modeli üstün/özel yeteneklilerde yaratıcılığı destekler mi? (Does STEAM integrated learning model support creativity ingifted/talented students?) *The Journal of Buca Faculty of Education,* 55, 140-153. https://doi.org/10.53444/deubefd.1207880

Çepni, S. (2018). *Kuramdan uygulamaya STEM eğitimi (STEM education from theory to practice).* Pegem Akademi.

Çimen, E., Çankaya, H., Çağlayan, F., Soylu, İ., & Erat, B. (2025). Okul öncesi eğitimde sanat ve yaratıcılığın önemi (The importance of art and creativity in preschool education). *International QMX Journal, 4*(3), 547–559. https://doi.org/10.5281/zenodo.15071380

Çorlu, M., S., Capraro, R., M., & Capraro, M. M. (2014). Introducing STEM Education: Implications for educating our teachers for the age of innovation. *Education and Science, 39*(171), 74-85.

Dikici, A. (2001) Sanat eğitiminde yaratıcılık (Creativity in art education). *Milli Eğitim Dergisi,*149.

Dugger, W. E. (2010, January). Evolution of STEM in the United States. In *Knowledge in Technology Education: Proceedings of the 6th Biennial International Conference on Technology Education: Volume One (TERC 2010)* (pp. 117-123). Surfers Paradise, QLD: Griffith Institute for Educational Research.

Gomez, C., & Ros, G. (2024). On the interrelationships between diverse creativities in primary education STEAM projects. *Thinking Skills and Creativity,* 51, 101456. https://doi.org/10.1016/j.tsc.2023.101456

Gülhan, F. & Şahin, F. (2018). The effects of STEAM (STEM+ Art) activities 7th grade students' academic achievement, STEAM attitude and scientific creativities, *International Journal of Human Sciences, 15*(3). https://doi.org/10.14687/jhs.v15i3.5430

Gürkaynak, İ., Üstel, F., & Gülgöz, S. (2008). *Eleştirel düşünme (Critical thinking).* Eğitim Reformu Girişimi.

Honey, M., Pearson, G., & Schweingruber, H. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. The National Academies Press. https://doi.org/10.17226/18612

İnce, K., Mısır, M. E., Küpeli, M. A., & Fırat, A. (2018). 5. sınıf fen bilimleri dersi yer kabuğunun gizemi ünitesinin öğretiminde STEM temelli yaklaşımın öğrencilerin problem çözme becerisi ve akademik başarısına etkisinin incelenmesi (Examining the effect of STEM-based approach on the problem-solving ability and academic success of students in teaching the enigma of the earth's crust unit of the 5th grade life). *Journal of STEAM Education, 1*(1), 64-78.

Jazariyah, J., Athifah, N. Z., Purnamasari, Y. M., & Lita. (2023). Fostering creative thinking in early learners through STEAM-based ecoprint projects. *Golden Age: Jurnal Ilmiah Tumbuh Kembang Anak Usia Dini, 8*(4), 311-322. https://doi.org/10.14421/jga.2023.84-10

Karatepe, Z. (2023). *STEAM temelli fen bilimleri etkinliklerinin, öğrencilerin akademik başarılarına ve bilimsel yaratıcılıklarına etkisi: 4. sınıf kuvvetin etkileri ünitesi örneği (The effects of STEAM-based science activities on academic achievement and scientific creativity of students: Example of the unit of 4th grade force effects)* [Unpublished master's thesis]. Kocaeli University.

Kızılırmak, B. (2018). Sınıf öğretmenlerinin görsel sanatlar dersi alan bilgisi öz yeterlik inançları (The self-sufficiency beliefs of classroom teachers with visual arts field information). *Gazi Journal of Education Sciences, 4*(3), 29-51. https://dx.doi.org/10.30855/gjes.2018.04.03.003

Laal, M., & Ghodsi, S. M. (2012). Benefits of collaborative learning. *Procedia-social and behavioral sciences*, *31*, 486-490. https://doi.org/10.1016/j.sbspro.2011.12.091

Madenci, A., & Yılmaz, İ. (2019). Sanatsal becerilerin STEAM etkinliklerinde yaratıcı düşünme, işbirliği ve tasarım becerileri üzerine etkileri (Effects of artistic skills on creative thinking, collaboration and design skills in STEAM activities) *Journal of Multidisciplinary Studies in Education, 3*(4), 52-63.

Mercin, L. (2019). STEAM eğitiminde sanatın yeri (Place of art in STEAM education). *Inonu University Journal of Art and Design, 9*(19), 28–41. https://doi.org/10.16950/iujad.514132

O'Neal, L. J., Gibson, P., & Cotten, S. R. (2017). Elementary school teachers' beliefs about the role of technology in 21st-centuryteaching and learning. *Computers in the Schools, 34*(3), 192-206. https://doi.org/10.1080/07380569.2017.1347443

Oh, J., Lee, J., & Kim, J. (2013). Development and application of STEAM based education program using Scratch: Focus on 6th graders' science in elementary school. In J. Park, J. Ng, H. Jeong, & B. Waluyo (Eds.), *Multimedia and Ubiquitous Engineering (Lecture Notes in Electrical Engineering,* (Vol. 240) (pp. 493–501). Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-94-007-6738-6_60

Park, N., & Ko, Y. (2012, September). Computer education's teaching-learning methods using educational programming language based on STEAM education. In J. J. Park, A. Zomaya, S. S. Yeo, & S. Sahni (Eds.), *Network and Parallel Computing. NPC 2012. Lecture Notes in Computer Science,* (Vol. 7513, pp. 320–327). Springer. https://doi.org/10.1007/978-3-642-35606-3_38

Partnership for 21st Century Learning. (2018*). P21 framework definitions.* Battelle for Kids. https://www.battelleforkids.org/networks/p21

Read, H. (1966). *Art and society.* Shocken Books.

Sousa, D. A., & Pilecki, T. (2018). *From STEM to STEAM: Brain-compatible strategies and lessons that integrate the arts*. Corwin Press. https://doi.org/10.4135/9781544357393

Tsupros, N., Kohler, R., & Hallinen, J. (2009). STEM education: A project to identify the missing components. *Intermediate Unit,* 1,11-17.

Ulus, H. (2024). *Sanat eğitimi STEAM & yaratıcılık (Art Education STEAM & Creativity).* PA Paradigma Akademi Publications.

URL-1. https://www.sciencebuddies.org/science-fair-projects/project-ideas/CE_p013/civil-engineering/building-the-tallest-tower

URL-2. https://www.sciencebuddies.org/science-fair-projects/project-ideas/Phys_p099/physics/balloon-powered-car-challenge

URL-3. https://www.sciencebuddies.org/science-fair-projects/project-ideas/CE_p027/civil-engineering/tallest-paper-tower-challenge

URL-4. https://www.sciencebuddies.org/science-fair-projects/project-ideas/Aero_p046/aerodynamics-hydrodynamics/how-far-will-paper-planes-fly

URL-5. https://www.sciencebuddies.org/science-fair-projects/project-ideas/Zoo_p066/zoology/bird-feeder

URL-6. https://www.sciencebuddies.org/science-fair-projects/project-ideas/ApMech_p053/mechanical-engineering/engineer-cell-phone-stand

URL-7. https://www.sciencebuddies.org/science-fair-projects/project-ideas/ApMech_p052/mechanical-engineering/build-ball-launcher

URL-8. https://www.sciencebuddies.org/science-fair-projects/project-ideas/Elec_p108/electricity-electronics/obstacle-detecting-glasses

URL-9. https://www.sciencebuddies.org/science-fair-projects/project-ideas/PlantBio_p055/plant-biology/arduino-automatic-plant-watering

Viereck, G. S. (1929, October 26). *What life means to Einstein*. *The Saturday Evening Post*. https://www.saturdayeveningpost.com/2010/03/imagination-important-knowledge/

Vurucu Şahin, C., & Şahin, F. (2020). Erken çocukluk döneminde bilim ve mühendislik uygulamalarının öğrencilerin karar verme ve problem çözme becerilerine etkisi (The impact of science and engineering practices on students' decision making and problem solving skills in early childhood). *Journal of STEAM Education, 3*(1), 1–19.

Yakman, G. (2008). STΣ@M education: An overview of creating a model of integrative education. In M. J. de Vries (Ed.), *Pupils' Attitudes Towards Technology (PATT-19) Conference Proceedings* (pp. 335–358). ITEEA.

Yeşilyurt, E. (2020). Yaratıcılık ve yaratıcı düşünme: Tüm boyut ve paydaşlarıyla kapsayıcı bir derleme çalışması (Creativity and creative thinking: A comprehensive review study with all dimension and stakeholders). *OPUS International Journal of Society Researches*, *15*(25), 3874-3915. https://doi.org/10.26466/opus.662721

Yıldırım, P. (2023). *Fen bilimleri dersinde uygulanan STEM ve STEAM etkinliklerinin 7. sınıf öğrencilerinin akademik başarılarına, motivasyonlarına, yaratıcılıklarına ve girişimciliklerine etkisinin incelenmesi: Karma yöntem araştırması (Investigation of the effects of STEM and STEAM activities applied in the science course on the academic achievement, motivation, creativity and entrepreneurship of 7th grade students: Fully integrated mixed method research).* [Unpublished doctoral dissertation]. Atatürk University.

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Chapter 9

Innovation and Entrepreneurship Integration in STEM Education: eSTEM

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Chapter Highlights

The following points summarise the core rationale, key components, and key implementation challenges of integrating entrepreneurship into STEM education (E-STEM), highlighting its role in fostering innovation, real-world problem solving, and sustainable educational practices.

- Importance of STEM Education – Emphasises STEM's role in developing critical thinking and problem-solving skills essential for global competitiveness and societal progress.
- STEM and the Entrepreneurial Mindset (E-STEM) – Highlights how entrepreneurial thinking complements STEM by fostering creativity, adaptability, and innovation in real-world problem solving.
- Technology-Driven STEM Entrepreneurship – Examines the role of emerging technologies in enabling innovative STEM-based entrepreneurial solutions.
- Integrating Entrepreneurship into STEM Education – Focuses on project-based learning, design thinking, and teacher preparation as key strategies for effective E-STEM integration.
- Frameworks, Challenges, and Future Needs – Discusses theoretical models, key integration challenges, and the need for context-sensitive instructional models to support scalable E-STEM implementation.

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Introduction

In today's technology-driven world, it is significant to possess a unique set of skills such as critical thinking, argumentation, decision-making, and problem-solving (Deveci & Seikkula-Leino, 2023). These skills enable individuals to analyze complex situations, evaluate multiple perspectives, and develop effective solutions (Deveci & Seikkula-Leino, 2023; Ozyazici et al., 2025). While these skills are fundamental in STEM fields, where innovation often depends on the ability to approach challenges analytically and creatively, they are also essential in social and everyday life. For instance, navigating workplace dynamics, making personal financial decisions, or assessing information in the media, individuals use these skills in their daily life. These skills allow us to make informed choices and respond strategically to problems. Current literature further emphasizes that these competencies are not only vital in technical and scientific domains but also serve as foundational elements of entrepreneurial thinking (Mitchelmore & Rowley, 2010). Literature shows that entrepreneurship requires individuals to identify opportunities, manage uncertainty, and develop strategies for bringing innovative ideas to fruition all of which rely on these cognitive and problem-solving abilities (Deveci, & Seikkula-Leino, 2023). As a result, it can be concluded that there is a strong and mutually reinforcing link between STEM education and the entrepreneurial mindset, highlighting the need for educational programs that cultivate both technical expertise and adaptive, innovation-oriented thinking. Recently, some researchers have examined STEM students' entrepreneurial intentions (Shahin et al., 2021) as they can be seen as innovators and future scientists, developing creative products, securing patents, and driving progress in their fields. Moreover, with the growing recognition of the connection between entrepreneurship and STEM, universities and colleges have begun to integrate courses such as entrepreneurship, entrepreneurial thinking, and business fundamentals into their STEM curricula (Ewim, 2023). For instance, The NSF also supports STEM entrepreneurship through various initiatives, including the I-Corps program (Nnakwe, et al., 2018), Entrepreneurial Fellowships, and SBIR/STTR grants.

In today's world, entrepreneurship does not only mean running a business (Pozen, 2018), it is also about fostering innovation. In this context, the entrepreneurial mindset has often been emphasized in engineering literature, as engineering majors focus on designing, innovation, creation and building structures (Bosman, 2018). However, by considering the required skills for all STEM majors, including argumentation, data analysis, critical thinking, innovation, there is great potential for all STEM students—including those in chemistry, physics, and related disciplines—to transform their ideas into innovative solutions that address real-world challenges. Unlike the predominant focus on entrepreneurial intentions and mindset among business and engineering students, there is a gap in the literature suggesting that the perspectives, ideas, career developments of all STEM students should be examined (Ozyazici et al., 2025).

We see that entrepreneurship education literature focuses on business majors. Also, most research is limited to applying quantitative surveys, not validated for STEM students specifically and they do not provide qualitative insights into students' entrepreneurial mindset, experiences, challenges, and barriers. For instance, research shows that female STEM entrepreneurs face barriers such as masculine-dominated environments, limited access to funding, gender bias and stereotypes, work–life balance struggles, and the challenge of navigating social and cultural norms (Yusif et al., 2024). There is a need to discover more on this and provide more deeper understandings on STEM entrepreneurs and their experiences. Moreover, literature is also missing how to integrate structured EE programs into STEM curricula, in a way that all STEM students can benefit. While many colleges are integrating EE into their curricula, we still have limited knowledge about design, its effectiveness, long-term impacts, and potential career path changes. In addition, more research is needed on interventions and students' perspectives before and after these interventions. It is also important to consider instructional design approaches, such as the ADDIE model (Muruganantham, 2015) and to apply relevant frameworks to ensure that EE is integrated into STEM curricula at an appropriate and effective level.

Overall, STEM and entrepreneurship are closely connected, as both rely on innovation, problem solving, and applying knowledge to real-world challenges. Yet, entrepreneurship is often misunderstood and reduced to stereotypes such as wealth-seeking or college dropout success stories. In contrast, STEM entrepreneurship highlights how scientific and technological expertise can be used to meet diverse social needs and drive inclusive progress. Recognizing this link is essential for reimagining entrepreneurship as not only an economic activity but also a pathway for social impact and sustainable innovation. This chapter will explore the intersection of STEM and entrepreneurship, highlighting how entrepreneurial thinking can enrich scientific and technological innovation. It will examine key theoretical frameworks and methodological approaches that connect these domains, while also identifying the challenges that arise when integrating entrepreneurship into STEM education and practice. Finally, the chapter will discuss strategies and methods to address these challenges, offering insights into how educators, researchers, and practitioners can foster more sustainable and impactful connections between STEM and entrepreneurial pathways.

Importance of Science Education and STEM Education

Science education mainly and fundamentally aims to foster scientific literacy, a skill that is increasingly vital for navigating the complexities of contemporary society (Yacoubian, 2018). Scientific literacy not only enables individuals to make informed personal and civic decisions but also equips them to critically examine the accuracy of claims circulating in public discourse (Priest, 2013). In today's media-driven world, the prevalence of misinformation and pseudoscience has become a growing concern (Impey, 2024). The rapid spread of unverified information through digital platforms makes it easy for individuals to accept claims without question, particularly when media literacy and critical thinking skills are lacking. As a result, many people tend to believe what they encounter online or in popular culture without thoroughly evaluating or analyzing its validity, which is also related to lack of scientific literacy.

As we navigate global challenges like climate change, pandemics, and rapid technological advancements, individuals must be equipped to skills such as critical thinking, argumentation and make reasoned judgments (Erdogan et al., 2017). STEM education, particularly at the higher education level, plays a crucial role in cultivating these capabilities (Erdogan et al., 2017). It fosters essential 21st-century skills such as critical thinking, problem-solving, and evidence-based argumentation (Lamb et al., 2017), skills that are emphasized in STEM.

Lastly, STEM education is a driver of economic growth and innovation. A well-prepared STEM workforce fuels technological advancement, scientific discovery, and entrepreneurship. However, despite its importance, STEM education faces significant challenges, high dropout rates remain a persistent concern, with fewer than 40% of students who begin college intending to major in STEM completing their degrees in these fields (Eagan et al., 2014; Sithole, et al., 2017). The reason for this could be lack of instructional strategies such as mentorship, culturally responsive teaching, and the creation of supportive learning environments. Ultimately, strengthening STEM education in higher education is not just about producing more scientists and engineers, it is about empowering all students with the tools to understand the world around them, contribute meaningfully to society, as well as economy.

Goals of STEM Education

The goals of STEM education extend beyond teaching science, technology, engineering, and mathematics content. A STEM-literate student should be able to think critically, ask meaningful questions, and apply knowledge to solve real-world problems (Ah-Namad & Osman, 2018). STEM education also emphasizes developing problem-solving skills, curiosity, creativity, teamwork, and communication, enabling students to collaborate effectively and adapt to emerging industries. In engineering contexts, students are encouraged to design solutions to authentic challenges. Teachers play a central role in this process by facilitating hands-on learning experiences that make lessons relevant and engaging. Additionally, STEM education fosters resilience, adaptability, ethical reasoning, and digital literacy. Collectively, these competencies prepare students not only for future careers but also for active and responsible citizenship

STEM education, especially in the twenty-first century, aims to prepare students not only with technical knowledge but also with the skills, attitudes, and competencies necessary to thrive in an increasingly complex, interconnected, and innovation-driven world. However, as Lin et al. (2022) noted, there is still no universal consensus among educators and researchers on the specific goals of STEM education, which makes its promotion and implementation challenging. A survey of 645 Taiwanese secondary STEM teachers showed broad support for 17 competencies such as creativity, critical thinking, and problem-solving, though entrepreneurial skills were less emphasized (Lin et al., 2022). The authors argue entrepreneurship should be prioritized in tertiary STEM education to prepare students for diverse careers. They also found that teachers' willingness to adopt integrative STEM approaches increases with institutional support. Similarly, Jannini et al. (2024) reported that supportive cultural and institutional environments foster mastery orientations in undergraduates, while anxiety hinders engagement. Together, these findings highlight the need for STEM goals to address both cognitive and affective domains, building perseverance, adaptability, and resilience alongside achievement. These findings show the need for STEM education goals to address both cognitive and affective domains, fostering perseverance, adaptability, and resilience alongside academic achievement.

Another element that we emphasize in terms of STEM education goals is building critical media literacy. Students today are surrounded by media that strongly shapes how people see science and technology. Without the ability to question sources and check facts, it is easy to believe misinformation. For instance, critical media literacy helps students analyze information carefully, spot biases, and recognize when claims are not supported by evidence (Kellner & Share, 2019). By combining STEM education with media literacy, students learn both the technical skills and the critical awareness needed to understand the world around them. This approach ensures that they are prepared not only to succeed in STEM careers but also to make thoughtful decisions in a society filled with complex information.

The link between STEM and Entrepreneurial Mindset (E-STEM)

The entrepreneurial mindset connects very closely with many of the main goals of STEM education. Having an entrepreneurial mindset means being able to see opportunities, use available resources wisely, and create something that has value in different areas of life (Olawale et al., 2020). It is not only about starting a business but also about thinking creatively, solving problems, and bringing new ideas to real situation (Kuschell et al., 2020). Skills such as creativity, problem-solving, and innovation are also at the heart of STEM education. In addition, developing an entrepreneurial mindset helps students build important qualities such as adaptability, resilience, and collaboration, which prepare them for challenges in both their careers and daily lives (Adeoye et al., 2024). One way to build this mindset is through experiential and problem-based learning, where students learn by doing rather than only by reading or listening. For example, Olawale et al. (2020) describe an engineering design lab model where students worked on authentic, real-world problems. In this setting, students not only applied their STEM knowledge but also practiced working as a team, thinking in creative ways, and reflecting on their learning with the help of mentors. This kind of approach shows how STEM education and entrepreneurship can come together, giving students experiences that are practical, meaningful, and closely connected to the real world.

Literature shows that entrepreneurship and STEM are interconnected, with STEM disciplines driving innovation and problem-solving (Deveci & Seikkula-Leino, 2023). However, it is important to first define entrepreneurship and entrepreneurial mindset. In literature, entrepreneurship is generally associated with individuals who possess distinct abilities, particularly those that drive innovation (Gartner, 1990). It is a dynamic process, and it is characterized by creativity, developing and implementing new ideas and solutions (Kuratko et al., 2021). Furthermore, an entrepreneurial mindset enables individuals to identify opportunities amid uncertainty and complexity, transforming challenges into possibilities (Kuratko, 2020). Developing an entrepreneurial mindset within STEM education can empower students to translate innovative ideas into viable solutions, address complex challenges, and identify market opportunities (Deveci & Seikkula-Leino, 2023; Galloway et al., 2006), which our society needs. Entrepreneurship provides opportunities for STEM graduates to apply their technical skills and knowledge in innovative and dynamic ways (Zahra et al., 2006). The term entrepreneurial mindset is often associated with engineering education. However, in reality, all STEM students have the potential to turn their ideas into practical solutions (Nguyen et al., 2019), especially when we look at the founders of STEM-related companies. STEM graduates often perceive fewer career options than those in other fields (Jelks & Crain, 2020), which may increase their willingness to explore alternative careers (Gilmartin et al., 2019) and STEM entrepreneurship could provide new career opportunities that extend beyond the conventional roles associated with STEM, allowing graduates to apply their skills in innovative ways. STEM students frequently excel in leadership, innovation, and problem-solving (Li & Li, 2023), enabling them to address complex challenges entrepreneurially. Research shows that nonbusiness students, particularly in science and engineering, can successfully transform ideas into viable ventures by developing entrepreneurial skills (Åstebro et al., 2012). Moreover, an entrepreneurial mindset could enable individuals to identify opportunities (Hölzner & Halberstadt, 2022), this aligns with STEM goals, requiring critical thinking and problem-solving (Ewim, 2023). Entrepreneurship is not limited to business students but is accessible to anyone with interest (Ewim, 2023). Studies highlight its strong link to STEM, showing how fostering this mindset bridges the gap between innovation and market application while developing key skills like opportunity recognition and strategic planning (Deveci & Seikkula-Leino, 2023; Kuschel et al., 2020).

Overall, the overlap between entrepreneurial mindset, creativity, argumentation, evaluation skills, and problem-solving reflects a shared objective of STEM education: to equip learners with the capacity to generate novel ideas, address complex problems, and contribute meaningfully to society. In a rapidly evolving global economy, these interconnected competencies are not supplementary but essential for ensuring that STEM graduates can lead innovation across sectors. This integration of entrepreneurship into STEM has increasingly been recognized as E-STEM, highlighting how entrepreneurial practices can enhance traditional STEM competencies.

Technology in STEM Entrepreneurship

Technology-driven entrepreneurship can show how STEM knowledge can be transformed into practical innovations that address real needs. Examples such as smart swim goggles, LED-equipped bike helmets, 3D-printed prosthetics, drone delivery of medical supplies, and sustainable textiles highlight how technology fosters both economic growth and social good. By linking scientific knowledge with entrepreneurial thinking, STEM professionals learn to spot unmet needs, apply solutions, and build scalable ventures that generate lasting impact.

Integrating Entrepreneurial Education (EE) into STEM

Universities play a pivotal role in shaping entrepreneurial mindsets. Studies have shown that EE fosters students' ability to act on their ideas and expand their career prospects (Klofsten et al., 2020; Shane, 2008). Institutions that promote EE contribute to the creation of entrepreneurial ecosystems, cultivating cultures of innovation that support future economic growth (Guerro et al., 2016; João & Silva, 2020). In the context of STEM education, incorporating EE aligns with its foundation because it could enhance students' capacity for innovative thinking and real-world problem solving. While engineering education has made notable progress in integrating EE through experiential learning and co-curricular programs (Lei et al., 2023), gaps remain in its implementation across other STEM disciplines such as biology and chemistry.

Recent literature shows EE research is becoming more interdisciplinary, yet contributions from science and technology disciplines are still limited (Tiberius & Weyland, 2023). Addressing these gaps requires not only quantitative assessments of EE outcomes but also qualitative exploration of students' experiences and perceptions (Ceyhan & Tillotson, 2020; Zhao & Zhang, 2021). Lastly, the effectiveness of EE varies depending on factors such as students' academic majors, gender, nationality, and level of education. For example, while French and Polish students reported positive outcomes after EE courses, male German students showed less favorable results, illustrating the need for context-specific pedagogical strategies (Packham et al., 2010). These findings are consistent with the Theory of Planned Behavior (Ajzen, 1991), which posits that attitudes influenced by education can shape intentions and ultimately behavior. Although research on integrating EE into STEM education is growing, the number of studies remains limited (Yu, Zheng, & He, 2025). It can be concluded that entrepreneurial and STEM education share a close connection, as they are mutually beneficial and reinforcing.

Bringing EE into STEM helps create a more complete learning experience, where students develop creativity, problem-solving, and practical skills while also preparing for future careers and industries.

Yu et al. (2025) analyzed 31 studies on entrepreneurial education in STEM published between 2012 and 2023 across thirteen countries. The United States contributed the most with 36% (11 studies), followed by Turkey with 19% (6 studies). Smaller contributions came from the United Kingdom, Malaysia, and Italy. These results reflect the field's international scope as well as its concentration in developed countries. Methodologically, qualitative designs were most prevalent (58.1%), followed by mixed methods (32.3%), and then quantitative studies (29.0%). Case studies were the most common, and interviews, used in six studies, were valuable for capturing students' perspectives on how entrepreneurial education shapes STEM learning. Participants ranged from primary school students to doctoral candidates, with the largest group being undergraduates (13 studies). Teachers were well represented, especially in-service teachers (16 studies). However, there was limited attention to pre-service teachers and STEM undergraduates, who are central to building future STEM capacity. More research with these populations is needed to guide classroom integration and workforce preparation. Overall, future studies should address the specific needs of STEM students by combining qualitative and quantitative approaches and exploring instructional design strategies for incorporating entrepreneurial education into higher education curricula.

Integrating entrepreneurship into STEM education, often referred to as E-STEM, presents both opportunities and challenges, particularly within higher education. STEM intervention programs, STEM-related academic departments, and business schools each have the potential to incorporate entrepreneurial elements into their curricula. Doing so not only supports students' career trajectories but also equips them with essential entrepreneurial skills, which are increasingly necessary in today's innovation-driven economy. Embedding entrepreneurship in STEM programs can help students move beyond technical expertise to become innovators capable of translating ideas into real-world solutions. The importance of such integration is reflected in initiatives like the U.S. National Science Foundation's Entrepreneurial Fellowships for engineers and scientists, launched in 2022 through a $20 million investment in partnership with Activate.org. This program supports fellows from diverse backgrounds to transform research breakthroughs into products and services with broad societal impact. However, despite these advancements, integration remains uneven, often hindered by disciplinary silos, lack of cross-department collaboration, and limited institutional resources. Globally, there is growing momentum in E-STEM, but efforts vary widely. India's tinkering labs in over 10,000 K-12 schools are fostering early STEM entrepreneurship, Germany is expanding youth entrepreneurship labs, and Europe is funding hybrid STEM-business ventures. In the United Kingdom, commercialization of scientific breakthroughs is becoming a policy priority. Yet, these examples also highlight disparities in access, resources, and scalability, underscoring the need for sustained investment, institutional alignment, and cross-sector partnerships to fully realize the potential of E-STEM worldwide.

Literature highlights the importance of STEM intervention programs for broadening participation and supporting student success in science and engineering (Ceyhan & Tillotson, 2020; Rodriquez et al., 2020). Embedding entrepreneurship education (EE) within these programs can further enhance students' career development by expanding their aspirations beyond traditional STEM pathways (Deveci & Seikkula-Leino, 2023). This integration is not about reinforcing the popular narrative of college dropouts becoming wealthy entrepreneurs; rather, it emphasizes preparing diverse STEM students to innovate and pursue meaningful careers that respond to both market demands and societal needs. Evidence from Souitaris et al. (2007) demonstrates that entrepreneurship programs can significantly increase the entrepreneurial intentions of science and engineering students, underscoring the value of educational interventions in shaping career decisions. Still, effective strategies for embedding EE into STEM programs remain underdeveloped (Deveci & Seikkula-Leino, 2023). Integrating EE across disciplines is essential for equipping students with the mindset and tools to address real-world problems (Kuschel et al., 2020; Nguyen et al., 2019). Yet, most existing studies focus primarily on business and engineering majors (Barba-Sánchez & Atienza-Sahuquillo, 2018; Kurata et al., 2023), overlooking the broader STEM population.

Recent work shows that universities are beginning to integrate EE into STEM curricula, though often only partially or in limited contexts. Research demonstrates that entrepreneurial practices can be incorporated through interdisciplinary approaches that connect knowledge across domains (Eltanahy et al., 2020). However, implementing E-STEM also presents significant challenges, including limited teacher training, heavy curricular demands, and difficulty in assessing entrepreneurial practices effectively.

Challenges of Integration E-STEM

STEM leaders have identified barriers such as limited teacher training in entrepreneurial learning, students' readiness to think beyond classroom tasks, and teachers' heavy curricular workloads. (Eltanahy et al., 2020). Additional challenges include assessing entrepreneurial practices effectively, sustaining student motivation, particularly in contexts where learners may lack incentives, and ensuring that outcomes extend beyond models to include innovative ideas, projects, or social services. These findings show the need for systemic support and interdisciplinary approaches to make E-STEM sustainable and impactful (Eltanahy et al., 2020).

Gender Issues

Women STEM entrepreneurs are crucial for driving innovation, fostering inclusivity, and addressing pressing societal challenges (George, 2024). Their unique perspectives often lead to more diverse, equitable, and creative solutions, enriching the innovation ecosystem. Women in entrepreneurship are more likely to address unmet needs, particularly those affecting women and underrepresented groups (Irwin, 2025) while challenging existing norms and fostering more dynamic, inclusive innovation. Despite these contributions, a significant gender gap persists in E-STEM, limiting the potential impact of women entrepreneurs. Closing this gap is not only a matter of equity but also of economic necessity. Research shows that increasing women's participation in entrepreneurship could significantly boost global development (Sajjad et al., 2020). However, systemic barriers hinder women's full participation in STEM entrepreneurship. Without targeted support, such as mentorship programs, equitable funding mechanisms, and inclusive curricula, women entrepreneurs remain underrepresented.

Their absence shows inequity, also reduces the diversity of perspectives necessary for addressing complex global challenges. Therefore, integrating gender equity into E-STEM initiatives is therefore essential for building a more innovative, and economically vibrant future. Moreover, challenges extend more broadly to include students from racially minoritized groups, low-income backgrounds, and first-generation college families. These students often face compounded barriers in accessing entrepreneurial ecosystems, mentorship opportunities, and early-stage funding. Without intentional design and targeted support, E-STEM risks reinforcing existing disparities rather than alleviating them (Ong et al., 2018).

Curricular Overload and Rigid Structures

STEM curricula are often already packed with technical and disciplinary requirements, leaving little flexibility to integrate entrepreneurship content. Faculty may resist adding entrepreneurship modules out of concern that they will displace essential disciplinary knowledge or extend students' already heavy workload (Borrego & Henderson, 2014). This structural rigidity creates one of the first barriers to embedding E-STEM within higher education.

Faculty Expertise and Training

Even when institutions make space for entrepreneurship content, many STEM instructors lack the formal training or confidence to teach entrepreneurial principles. As a result, programs often depend on external partners such as business schools or industry mentors, which can lead to inconsistency and uneven program quality (Baik et al., 2019). Developing faculty capacity is therefore critical for sustaining high-quality E-STEM initiatives.

Assessment and Measurement

Another significant challenge involves the evaluation of entrepreneurial education. Constructs such as entrepreneurial mindset, creativity, and innovation capacity are difficult to measure with conventional STEM assessment tools. Without valid and reliable instruments, it becomes challenging for institutions to demonstrate outcomes, secure funding, or justify the curricular space dedicated to E-STEM (Ozyazici et al., 2025).

Cultural Perceptions of Entrepreneurship

Within some academic contexts, entrepreneurship is perceived as less rigorous or even incompatible with the ideals of "pure" STEM research. Such cultural perceptions can reduce faculty buy-in and discourage students who fear that pursuing entrepreneurship may undermine their credibility as scientists or engineers (Feldman & Kenney, 2004). Changing these perceptions requires a cultural shift in how higher education values entrepreneurial pathways.

Theoretical Frameworks in STEM and Entrepreneurial Education

The development of entrepreneurial thinking among STEM students is often examined through the Theory of Planned Behavior (TPB) (Ajzen, 1991; Montes et al., 2023) and Social Cognitive Career Theory (SCCT) (Duong & St-Jean, 2024). TPB emphasizes the formation of entrepreneurial intentions by considering individuals' attitudes toward entrepreneurship, subjective norms, and perceived behavioral control. In contrast, SCCT focuses more broadly on career development pathways, highlighting how self-efficacy beliefs, outcome expectations, and environmental supports or barriers influence students' decisions and persistence in entrepreneurial careers (Tran & Von Korflesch, 2016). Despite their contributions, the literature shows limited use of SCCT in exploring the entrepreneurial mindset of STEM learners, creating opportunities for new research. Recent scholarship suggests that one theory alone may not fully explain the complex process through which STEM students develop entrepreneurial pathways. For example, Ozyazici et al. (2025) applied both SCCT and TPB in examining entrepreneurial career development, showing how these frameworks complement each other by addressing both intention formation and broader contextual influences. Integrating these perspectives provides a more holistic understanding of how STEM students' values, self-beliefs, and perceived opportunities shape their entrepreneurial goals. In this study, the authors also developed the STEM Entrepreneurship Career Development Measure (SECDM), a theoretically grounded instrument designed to capture the unique experiences and aspirations of STEM students in entrepreneurial contexts (Ozyazici et al., 2025).

The creation of SECDM has important implications for both research and practice. First, it fills a critical gap in measurement by offering a tool that accounts for the motivational, cognitive, and contextual factors emphasized in SCCT and TPB. Second, it provides a foundation for evaluating the effectiveness of entrepreneurship-focused STEM intervention programs. With valid measures, educators and program designers can more accurately assess changes in students' entrepreneurial intentions, self-efficacy, and outcome expectations over time. This, in turn, allows for the design of targeted instructional strategies and interventions that not only build entrepreneurial competencies but also address barriers faced by underrepresented groups. Furthermore, another set of measures, such as the Entrepreneurial Intention Questionnaire (Liñán & Chen, 2009), the Entrepreneurial Self-Efficacy Scale (Zhao et al., 2005), and entrepreneurial mindset scales (Adebusuyi et al., 2022; Hirschi, 2014), are also very important in the entrepreneurship literature, and they need to be tested with STEM student populations to evaluate their relevance and validity in this context. Doing so would expand the methodological base of STEM entrepreneurship research and provide stronger tools for assessing intervention programs, ensuring that instructional strategies effectively foster entrepreneurial intentions, self-efficacy, and equitable opportunities for diverse learners.

Another framework to add or follow could be the ADDIE framework

(Analysis, Design, Development, Implementation, and Evaluation), that provides a systematic model for integrating entrepreneurship education into STEM curricula (Muruganantham, 2015). In the Analysis phase, educators can identify students' existing entrepreneurial knowledge, intentions, and contextual barriers through surveys, interviews, or diagnostic assessments. The Design and Development phases allow for the creation of targeted interventions—such as project-based learning, mentorship opportunities, or case studies—that explicitly connect STEM knowledge with entrepreneurial skills. During Implementation, these strategies can be embedded into STEM courses, intervention programs, or co-curricular activities, ensuring that entrepreneurship is taught not as an add-on but as part of disciplinary learning. Finally, the Evaluation phase ensures continuous improvement by assessing changes in students' entrepreneurial self-efficacy, intentions, and outcomes, while also highlighting areas for refinement. Applying ADDIE in this way helps bridge theory and practice, ensuring that interventions are both evidence-based and responsive to the diverse needs of STEM learners. Moreover, while quantitative studies guided by the Theory of Planned Behavior (Ajzen, 1991) dominate the field, qualitative work is necessary to capture students' lived experiences (Mensah et al., 2021; Montes et al., 2023). Listening to students' voices is vital for designing interventions that cultivate entrepreneurial mindsets, creativity, and innovation, while also supporting the career aspirations of the future STEM workforce.

Need for Specific Models

Entrepreneurship education within STEM programs requires carefully designed instructional models that move beyond business-oriented frameworks to address the specific needs of STEM students. Effective strategies often include online learning modules that introduce entrepreneurship concepts, opportunities to interact with guest speakers and industry professionals, and structured peer engagement through collaborative projects or discussion forums. These approaches help students connect theoretical content to practical, real-world applications, thereby fostering entrepreneurial thinking within STEM contexts.

Embedding entrepreneurship education into existing seminar courses represents another effective strategy, as it ensures accessibility and contextual relevance. Rather than positioning entrepreneurship as an add-on, integrating it into existing coursework provides structured opportunities for reflection and engagement. This approach aligns with learner-centered instructional design principles that emphasize relevance, authenticity, and active learning (Merrill, 2002). Furthermore, adopting a systems-thinking perspective acknowledges that entrepreneurship education is shaped not only by the classroom environment but also by institutional policies, career services, and external networks. Equity and access must be considered central design features. Research shows that female-friendly curricula and sensitivity to women's perspectives can help address persistent gender gaps in STEM (Cheng & Lo, 2022). At the same time, programs must intentionally design for the inclusion of first-generation college students, students from low-income backgrounds, and racially minoritized groups to ensure that entrepreneurship education opportunities are not disproportionately available to those with more resources or privilege. Such inclusive approaches require continuous evaluation to avoid reinforcing inequities that already exist in STEM higher education.

Finally, scholars emphasize that entrepreneurship education should be democratized and accessible across disciplines, not limited to business students. Entrepreneurial skills empower individuals to contribute socially and economically as proactive citizens, making entrepreneurship education a critical component of preparing students for participation in democratic societies (Ewim, 2023; Ribeiro et al., 2023).

Additionally, scalability and sustainability remain persistent concerns for entrepreneurship education in STEM. While guest speakers, industry partnerships, and mentoring programs are highly valued by students and shown to strengthen career readiness, such strategies often require significant financial resources, administrative coordination, and faculty time (Fayolle & Gailly, 2015). Without institutional commitment—such as funding for ongoing programming, recognition of faculty workload, and integration into long-term curricular planning—these initiatives risk being short-lived pilot efforts rather than durable transformations. Moreover, sustainable models must balance quality with reach; expanding entrepreneurship opportunities to a wider pool of students cannot come at the expense of program depth or individualized support. Embedding entrepreneurship education within institutional priorities, including diversity and workforce development initiatives, offers one pathway for ensuring both longevity and equitable access.

Discussion

Recognizing the role of STEM entrepreneurship is crucial for changing how society perceives entrepreneurs. Too often, entrepreneurs are stereotyped as college dropouts chasing profit or as individuals focused only on building wealth. This narrow view overlooks the broader contributions of entrepreneurship, particularly when grounded in STEM. STEM entrepreneurs bring together scientific knowledge, technological skills, and an innovative mindset to address complex and diverse societal needs. Rather than fitting the stereotype, they create solutions that improve healthcare, education, sustainability, and equity. By highlighting the social and community-focused impact of STEM entrepreneurship, higher education and policy can help shift public perception: from seeing entrepreneurs as profit-driven to understanding them as problem-solvers, innovators, and leaders who respond to the needs of diverse populations. This reframing is essential to inspire the next generation of students to view entrepreneurship not only as a career option but as a pathway to social change and inclusive progress.

Overall, the literature consistently shows that STEM and entrepreneurship are deeply interconnected, particularly when considering the skills demanded in today's innovation-driven economy. Integrating entrepreneurship into STEM curricula not only prepares students for emerging career paths but also fosters critical competencies such as creativity, problem-solving, risk-taking, and adaptability (Adebusuyi et al., 2022; Yu et al., 2025). Many universities have already begun embedding entrepreneurial education into engineering, science, and technology programs, often through innovation hubs, maker spaces, or incubator programs that allow students to prototype and pitch their ideas (Hirschi et al., 2014). For instance, institutions such as MIT and Stanford have long blended engineering design with entrepreneurial training, while Europe's EIT InnoEnergy program explicitly links sustainable energy innovations with entrepreneurship to address global climate challenges (Yu et al., 2025). Importantly, this integration should not be confined to higher education alone. Preparing future teachers to incorporate entrepreneurial thinking into their practice can bring these skills to younger students, laying a foundation for innovation at earlier ages. Small-scale interventions, such as having middle school science students design low-cost water filtration systems, build simple apps, or experiment with sustainable materials, illustrate how entrepreneurial mindsets can be developed through authentic STEM problem-solving (Liñán & Chen, 2009). Globally, programs such as India's Atal Tinkering Labs or Singapore's national emphasis on innovation within STEM curricula demonstrate that entrepreneurial elements in STEM education empower students to become solution-seekers for real-world problems (World Bank, 2020). Thus, fostering entrepreneurial skills within STEM classrooms, whether at the university level or in middle schools, ensures that the next generation is prepared to translate scientific knowledge into scalable, socially impactful solutions, driving both economic growth and societal resilience.

Another important discussion point concerns how to design appropriate-level interventions or lesson plans that effectively integrate entrepreneurship into STEM learning. While the literature demonstrates the value of E-STEM integration, there is still a lack of systematic frameworks for instructional design that guide teachers in tailoring entrepreneurial content to different age groups and educational contexts (Yu et al., 2025). Designing interventions that are developmentally appropriate is essential: for instance, modules for middle school science may emphasize creativity, teamwork, and problem identification, whereas higher education interventions can include market analysis, prototyping, and venture creation (Adebusuyi et al., 2022). Some research has already experimented with such integrations. For example, Rauch and Hulsink (2015) developed entrepreneurship modules in engineering curricula that improved students' entrepreneurial self-efficacy and opportunity recognition. However, these studies remain relatively isolated, and more models are needed to provide teachers—both at K–12 and higher education levels—with clear strategies for weaving entrepreneurial elements into STEM lessons. Drawing from established instructional design approaches, such as ADDIE or Merrill's First Principles, could support the structured development of E-STEM curricula that balance content knowledge with innovation skills. Expanding this line of research would not only strengthen the evidence base but also equip educators with practical frameworks to embed entrepreneurial thinking meaningfully into science and engineering classrooms.

Conclusion

Entrepreneurship in STEM (E-STEM) is a promising but still developing area in education and research. Evidence shows that STEM and entrepreneurship share important skills such as critical thinking, problem solving, and the ability to apply knowledge in real-world settings. Yet, the current approaches to integrating entrepreneurship into STEM remain limited and often focus only on engineering students. To be effective, integration should consider students' majors, prior knowledge, academic level, and career intentions. Bringing entrepreneurship into STEM education does more than expand technical knowledge. It helps students become innovators who can turn ideas into solutions that support both economic growth and social progress. At the same time, several challenges must be addressed. Reliable assessment tools are lacking, which makes it difficult to measure outcomes and justify investment. Cultural views in some institutions still treat entrepreneurship as less rigorous than traditional STEM work, limiting support from faculty and students. Equity concerns also remain, especially for students from racially minoritized, first-generation, or low-income backgrounds who face barriers to resources and mentorship. Without targeted support, E-STEM could unintentionally reinforce these inequalities. Even so, the potential impact of E-STEM is clear. Embedding entrepreneurial pathways into STEM programs can open opportunities, broaden participation, and prepare students to contribute as active citizens in an innovation-driven world. Future progress depends on developing strong measurement tools, creating inclusive learning environments, and building stronger links between STEM fields and business education. Institutions also need to recognize and value entrepreneurial achievements alongside traditional academic success. E-STEM should not be seen as an optional addition but as a necessary part of preparing the next generation of scientists, engineers, and innovators. With intentional design and inclusive practices, higher education can foster entrepreneurial mindsets that enable students to lead change, address diverse needs, and shape both technological and social futures.

Recommendations

Future research and practice in STEM entrepreneurship education should prioritize validating existing entrepreneurship surveys with STEM student populations, as measures widely used in the literature may not fully capture their unique experiences. Combining theoretical frameworks such as TPB and SCCT can provide a more comprehensive understanding (Ozyazici et al., 2025) of intention formation and contextual influences, while methodological rigor should be strengthened by employing reliability indices like McDonald's omega, which offers a more robust estimate of internal consistency than Cronbach's alpha (Dunn et al., 2014). At the same time, educators and policymakers must work to change societal stereotypes that frame entrepreneurs as merely profit-driven, highlighting instead how STEM entrepreneurship can empower students across all disciplines, not just engineering, design innovative solutions that address diverse and pressing real-world problems. Such efforts can expand participation, foster inclusivity, and position STEM entrepreneurship as a pathway for both social impact and economic progress. Future research could talk more on qualitative findings on STEM entrepreneurship, design specific interventions for targeted groups, there is a lack of information about students, or workers personal experiences about STEM entrepreneurship and/or STEM entrepreneurship classes.

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References

Adebusuyi, A. S., Kolawole, S. O., Abu, H. S., Adebusuyi, O. F., & Ajulo, A. A. (2022). Predicting entrepreneurial and professional career mindsets in young Nigerian adults. Journal of Entrepreneurship in Emerging Economies, 14(6), 1096-1117.

Ajzen, I., 1991. The theory of planned behavior. Organ. Behav. Hum. Decis. Process. 50 (2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-

Ah-Namand, L., & Osman, K. (2018). Integrated STEM education: Promoting STEM literacy and 21st century learning. *Research highlights in STEM education*, 66-80.

Ardichvili, A., Cardozo, R., & Ray, S. (2003). A theory of entrepreneurial opportunity identification and development. *Journal of Business venturing*, *18*(1), 105-123.

Antonites, A. J. (2005). *An action learning approach to entrepreneurial creativity, innovation and opportunity finding* (Doctoral dissertation, University of Pretoria).

Ameh, O. (2024). Exploring the determinants of entrepreneurial intentions and career aspirations among science students: The role of educational experiences and career pathways *CUSTECH International Journal of Education*, *1*(2), 29-46.

Bandura, A., & Cervone, D. (1986). Differential engagement of self-reactive influences in cognitive motivation. *Organizational behavior and human decision processes*, *38*(1), 92-113.

Barba-Sánchez, V., & Atienza-Sahuquillo, C. (2018). Entrepreneurial intention among engineering students: The role of entrepreneurship education. *European research on management and business economics*, *24*(1), 53-61.

Bird, A. (1998). Dispositions and antidotes. *The philosophical quarterly*, *48*(191), 227-234.

Borrego, M., & Henderson, C. (2014). Increasing the use of evidence-based teaching in STEM higher education: A comparison of eight change strategies. Journal of Engineering Education, 103(2), 220-252.

Byers, T., Seelig, T., Sheppard, S., & Weilerstein, P. (2013). Its role in engineering education. The Bridge, 43(2), 35-40.

Casanova, J. R., Castro-López, A., Bernardo, A. B., & Almeida, L. S. (2023). The dropout of first-year stem students: Is it worth looking beyond academic achievement?. *Sustainability*, *15*(2), 1253. Cui, J., & Gu, L. (2024). The effect ` of entrepreneurial education on career choice intentions of college students: a social cognitive career theory approach. *Education+ Training*.

Cheng, M. F., & Lo, Y. H. (2022). Innovative STEM curriculum to enhance students' engineering design skills and attitudes towards STEM. In Concepts and practices of STEM education in Asia (pp. 117-137). Singapore: Springer Nature Singapore.

Duong, C. D., & St-Jean, É. (2024). Social cognitive career theory and higher education students' entrepreneurial intention: The role of perceived educational support and perceived entrepreneurial opportunity. Journal of Entrepreneurship, Management and Innovation, 20(1), 86-102.

Eltanahy, M., Forawi, S., & Mansour, N. (2020). Incorporating entrepreneurial practices into STEM education: Development of interdisciplinary E-STEM model in high school in the United Arab Emirates. Thinking Skills and Creativity, 37, 100697.

Erdogan, I., Ciftci, A., Yildirim, B., & Topcu, M. S. (2017). STEM education practices: examination of the argumentation skills of pre-service science teachers. *Journal of Education and Practice*, *8*(25), 164-173.

George, A. S. (2024). Bridging the gender gap in STEM: Empowering women as drivers of technological innovation. *Partners Universal Innovative Research Publication*, *2*(2), 89-105.

Hirschi, A., Freund, P. A., & Herrmann, A. (2014). The career engagement scale: Development and validation of a measure of proactive career behaviors. Journal of career assessment, 22(4), 575-594.

Merrill, M. D., Barclay, M., & van Schaak, A. (2008). Prescriptive principles for instructional design. Handbook of research on educational communications and technology, 173-184.

Montes, J., Ávila, L., Hernández, D., Apodaca, L., Zamora-Bosa, S., & Cordova-Buiza, F. (2023). Impact of entrepreneurship education on the entrepreneurial intention of university students in Latin America. *Cogent Business & Management, 10*(3), 2282793.

DeCoito, I., & Briona, L. K. (2023). Fostering an entrepreneurial mindset through project-based learning and digital technologies in STEM teacher education. In *Enhancing entrepreneurial mindsets through STEM education* (pp. 195-222). Cham: Springer International Publishing.

Deveci, İ., & Seikkula-Leino, J. (2023). The link between entrepreneurship and STEM education. In *Enhancing entrepreneurial mindsets through STEM* *education* (pp. 3-23). Cham: Springer International Publishing.

Doan, W., Jeff, V. and Ehrhardt, K. (2011), "An organizing framework for entrepreneurial intentions research: an integration and extension of dominant intent based models using social cognitive career theory", USA: Small Business Journal, Vol. 12.

Ewim, D. R. E. (2023). Integrating Business principles in STEM Education: fostering entrepreneurship in students and educators in the US and Nigeria. *IJEBD (International Journal of Entrepreneurship and Business Development)*, *6*(4), 590-605.

Hixson, C., Paretti, M., & Lesko, J. J. (2012, October). Work in progress: Integrating entrepreneurship into undergraduate engineering education. In *2012 Frontiers in Education Conference Proceedings* (pp. 1-2). IEEE.

Hynes, B., Costin, Y., & Richardson, I. (2023). Educating for STEM: Developing entrepreneurial thinking in STEM (Entre-STEM). In *Enhancing entrepreneurial mindsets through STEM education* (pp. 165-194). Cham: Springer International Publishing.

Irwin, K., McDowell, W., & Ribeiro-Navarrete, S. (2025). How can women entrepreneurs overcome funding challenges: the role of digitalization and innovation. *Venture Capital*, *27*(2), 225-247.

Kellner, D., & Share, J. (2019). *The critical media literacy guide: Engaging media and transforming education* (Vol. 2). Brill.

Kuschel, K., Ettl, K., Díaz-García, C., & Alsos, G. A. (2020). Stemming the gender gap in STEM entrepreneurship–insights into women's entrepreneurship in science, technology, engineering and mathematics. *International Entrepreneurship and Management Journal*, *16*(1), 1-15.

Lamb, S., Maire, Q., & Doecke, E. (2017). Key skills for the 21st century: An evidence-based review.

Lei, J., Indiran, L., Ramakrishna, Y., Raju, P., & Kohar, U. H. A. (2023). A systematic literature review on entrepreneurship intention among engineering students: Impact of personal, academic, and social factors. Handbook of Research on Designing Sustainable Strategies to Develop Entrepreneurial Intention, 1-28.

Liguori, E. W., Bendickson, J. S., & McDowell, W. C. (2018). Revisiting entrepreneurial intentions: a social cognitive career theory approach. *International Entrepreneurship and Management Journal*, *14*, 67-78.

Liñán, F., & Fayolle, A. (2015). A systematic literature review on entrepreneurial intentions: citation, thematic analyses, and research agenda. *International entrepreneurship and management journal*, *11*, 907-933.

Maheshwari, G., Kha, K. L., & Arokiasamy, A. R. A. (2023). Factors affecting students' entrepreneurial intentions: a systematic review (2005–2022) for future directions in theory and practice. *Management Revie Quarterly*, *73*(4), 1903-1970.

Mitchelmore, S., & Rowley, J. (2010). Entrepreneurial competencies: a literature review and development agenda. *International journal of entrepreneurial Behavior & Research*, *16*(2), 92-111.

Mensah, I. K., Zeng, G., Luo, C., Xiao, Z., & Lu, M. (2021). Exploring the predictors of Chinese college students' entrepreneurial intention. *Sage Open*, *11*(3), 21582440211029941.

Montes, J., Ávila, L., Hernández, D., Apodaca, L., Zamora-Bosa, S., & Cordova-Buiza, F. (2023). Impact of entrepreneurship education on the entrepreneurial intention of university students in Latin America. *Cogent Business & Management*, *10*(3), 2282793.

Muruganantham, G. (2015). Developing of E-content package by using ADDIE model. *International Journal of Applied Research*, *1*(3), 52-54.

Ndou, V., Secundo, G., Schiuma, G., & Passiante, G. (2018). Insights for shaping entrepreneurship education: Evidence from the European entrepreneurship centers. *Sustainability*, *10*(11), 4323.

Nguyen, A. T., Do, T. H. H., Vu, T. B. T., Dang, K. A., & Nguyen, H. L. (2019). Factors affecting entrepreneurial intentions among youths in Vietnam. *Children and Youth Services Review*, *99*, 186-193.

Nnakwe, C. C., Cooch, N., & Huang-Saad, A. (2018). Investing in academic technology innovation and entrepreneurship: Moving beyond research funding through the NSF I-CORPS™ program. *Technology & Innovation*, *19*(4), 773-786.

Ozyazici, G., Wang, Q., & Tillotson, J. W. (2025). Promoting Entrepreneurial Career Development in STEM: Developing and Validating a STEM Entrepreneurial Career Development Measure (SECDM). *Journal of Science Education and Technology*, 1-15.

Pandit, D., Joshi, M. P., & Tiwari, S. R. (2018). Examining entrepreneurial intention in higher education: An exploratory study of college students in India. *The Journal of Entrepreneurship*, *27*(1), 25-46.

Priest, S. (2013). Critical science literacy: What citizens and journalists need to know to make sense of science. *Bulletin of Science, Technology &*

Society, *33*(5-6), 138-145.

Ribeiro, T., Silva, J., Paz, M., Cardoso, A., Teles, N., Nogueira, C., & Ribeiro, T. (2023). Strengthening bridges between STEM education and entrepreneurship: pathways to societal empowerment towards sustainability. In *Enhancing Entrepreneurial Mindsets Through STEM Education* (pp. 25-47). Cham: Springer International Publishing.

Sajjad, M., Kaleem, N., Chani, M. I., & Ahmed, M. (2020). Worldwide role of women entrepreneurs in economic development. *Asia Pacific Journal of Innovation and Entrepreneurship*, *14*(2), 151-160.

Sampene, A. K., Li, C., Khan, A., Agyeman, F. O., & Opoku, R. K. (2023). Yes! I want to be an entrepreneur: A study on university students' entrepreneurship intentions through the theory of planned behavior. *Current Psychology*, *42*(25), 21578-21596.

Shahriar, M. S., Hassan, M. S., Islam, M. A., Sobhani, F. A., & Islam, M. T. (2024). Entrepreneurial intention among university students of a developing economy: the mediating role of access to finance and entrepreneurship program. *Cogent Business & Management*, *11*(1), 2322021.

Shahin, M., Ilic, O., Gonsalvez, C., & Whittle, J. (2021). The impact of a STEM-based entrepreneurship program on the entrepreneurial intention of secondary school female students. *International Entrepreneurship and Management Journal*, *17*(4), 1867-1898.

Subagio, H. (2023). Integrating Diffusion Perspective of Total Quality Management Improvement in SMEs Indonesia Sector: a Bibliometric Analysis. *Journal of Entrepreneurship and Business*, *4*(2), 82-92.

Sithole, A., Chiyaka, E. T., McCarthy, P., Mupinga, D. M., Bucklein, B. K., & Kibirige, J. (2017). Student attraction, persistence and retention in STEM programs: Successes and continuing challenges. *Higher Education Studies*, *7*(1), 46-59.

Tran, A. T., & Von Korflesch, H. (2016). A conceptual model of social entrepreneurial intention based on the social cognitive career theory. *Asia Pacific Journal of Innovation and Entrepreneurship*, *10*(1), 17-38.

Wang, X. H., You, X., Wang, H. P., Wang, B., Lai, W. Y., & Su, N. (2023). The effect of entrepreneurship education on entrepreneurial intention: mediation of entrepreneurial self-efficacy and moderating model of psychological capital. *Sustainability*, *15*(3), 2562.

Yacoubian, H. A. (2018). Scientific literacy for democratic decision-making. *International Journal of Science Education*, *40*(3), 308-327.

Yasa, N. N. K., Sukaatmadja, I. P. G., Santika, I. W., Suparna, G., Ekawati, N. W., Rahmayanti, P. L. D., ... & Muna, N. (2023). The Role of Entrepreneurship Orientation and Entrepreneurship Attitudes in Mediating the Effect of Entrepreneurship Education on Students' Entrepreneurship Intention. *Journal of Higher Education Theory and Practice*, *23*(10).

Yusif, S., Abunyewah, M., & Erdiaw-Kwasie, M. O. (2024). Challenges faced by minority technology entrepreneurs—women IT entrepreneurs in south africa post-apartheid era. *Journal of International Entrepreneurship*, 1-37.

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STEM Enrichment Through FSM: A Graduate-Led Summer Camp Model for Equitable Learning in Math and Science

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Chapter Highlights

The following highlights summarise the design, implementation, and impact of the Foundations in Science and Mathematics (FSM) program as a sustainable and equity-focused STEM outreach model, highlighting its role in broadening access to STEM learning and supporting graduate instructor development.

- Program Origins and Purpose – Introduces FSM as a graduate-student-led outreach program launched in 2010 at Indiana University, aimed at broadening access to STEM education for middle and high school students.
- Curriculum and Pedagogical Approach – Highlights student-centred, practice-oriented enrichment courses across mathematics, science, robotics, and coding, connecting academic rigor with real-world relevance.
- Program Organization and Partnerships – Examines key organisational elements, including instructor recruitment, curriculum planning, and collaboration with local schools and families.
- Equity and Accessibility Measures – Describes strategies such as hybrid delivery formats, financial support, and cross-departmental collaboration to ensure inclusive participation.

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Introduction

STEM education has increasingly been recognized as central to preparing students for the demands of the 21st century workforce and society. Beyond traditional classroom instruction, out-of-school learning opportunities such as summer camps have become popular vehicles to foster students' interest, motivation, and achievement in science, technology, engineering, and mathematics (STEM). Researchers have examined these informal learning environments for decades, highlighting their potential to counteract summer learning loss and promote long-term engagement with STEM disciplines. A foundational concern addressed by summer programs is the phenomenon of summer learning loss, in which students' academic achievement declines during extended school breaks. Cooper et al. (1996) provided one of the most comprehensive early reviews, demonstrating through a meta-analysis that students typically lose achievement in mathematics and reading during summer vacation, with losses disproportionately affecting students from lower socioeconomic backgrounds. This finding has since been widely cited to justify the design and implementation of summer enrichment programs, including those focused on STEM, as a means of mitigating educational inequalities (Alexander et al., 2007).

Building on this foundation, scholars have emphasized the role of STEM camps in sustaining or even enhancing students' academic trajectories during the summer. For example, Young et al., (2017), in their meta-analysis, found that out-of-school STEM experiences significantly increased students' interest and attitudes toward STEM fields, providing evidence that structured programs beyond the school day can shape career aspirations and motivation. Similarly, Drey (2016) documented the positive influence of STEM summer camps on students' motivation and interest in mathematics and science, underscoring the motivational power of hands-on and inquiry-based activities.

Recent research continues to explore the ways in which STEM summer programs can develop both content knowledge and affective outcomes. Tekbıyık et al. (2022) investigated a robotics-focused summer camp and found that students not only developed more sophisticated knowledge structures but also reported stronger STEM career interests, suggesting the importance of thematic and technology-rich camp models. Franks and McGlamery (2021) extended this conversation to preservice teachers, showing that teaching in a summer STEM camp enhanced mathematics teaching self-efficacy among future educators. This dual impact on both students and instructors illustrates the broader educational value of summer

STEM initiatives. In addition, other studies have explored organizational and pedagogical aspects of STEM camps. Davis and Hardin (2013), for instance, provided practical guidelines for structuring STEM camps that are both engaging and inclusive, especially for students with exceptional needs. Their work emphasizes that the design of these camps is as critical as their content, requiring attention to accessibility, differentiation, and sustainability. These perspectives resonate with more recent calls to align STEM camps with authentic scientific and engineering practices, ensuring that students experience STEM in ways that mirror professional inquiry (National Research Council, 2012).

Together, these strands of research demonstrate that STEM summer programs are not isolated interventions but rather part of a growing body of educational practice and scholarship. Meta-analyses (Cooper et al., 1996; Young et al., 2017), empirical studies (Drey, 2016; Tekbıyık et al., 2022), practitioner-oriented guides (Davis & Hardin, 2013), and studies of teacher development (Franks & McGlamery, 2021) all affirm the importance of summer STEM camps as both a response to learning loss and a catalyst for long-term engagement in STEM. By situating our work within this literature, we highlight FSM's summer camp model as both part of this broader tradition and a unique case of STEM enrichment situated within a university-community partnership.

Origins and Purpose of FSM

The Foundations in Science and Mathematics (FSM) program began with a straightforward question: How can graduate students in STEM and STEM education meaningfully serve their local community? In 2010, a small group of Indiana University graduate students took this question to heart and created a summer program designed to provide high-quality, affordable STEM learning opportunities for middle and high school students in the Bloomington area. Since its inception, the program's mission has remained clear to build an accessible, inclusive, and intellectually stimulating summer environment for young people eager to explore science and mathematics.

From the outset, FSM was grounded in values of access, equity, and collaboration. The program was never intended simply to "fill gaps" in academic preparation; rather, it sought to invite students into a space where STEM could be experienced as engaging, relevant, and empowering. The emphasis extended beyond improving test scores to helping students develop confidence as learners and problem solvers, while also providing them with instructors who were close in age but deeply knowledgeable and enthusiastic about their fields.

What makes FSM distinctive is its graduate-student-led structure. Unlike many outreach efforts initiated and overseen primarily by faculty or institutional administrators, FSM has been carried forward by the energy and commitment of graduate students and advanced undergraduates. These individuals have guided the program's planning, teaching, and day-to-day operations. This bottom-up approach has allowed FSM to remain flexible and responsive, with its courses, teaching strategies, and outreach activities evolving directly from the insights and experiences of those actively engaged in the work.

Over time, the program has grown in both scope and impact. Course offerings have expanded, partnerships with different university units have strengthened, and FSM has reached a wider pool of students across the region. As the program has matured, so too has its purpose. Beyond enriching the learning of participating students, FSM has become an important site for the professional development of instructors. Graduate students gain first-hand experience in curriculum design, classroom teaching, and educational leadership, preparing them for future careers in education and academia. In this way, FSM contributes not only to the development of the next generation of STEM learners but also to the preparation of the next generation of STEM educators.

Program Design and Operations

Instructor Recruitment and Preparation

A central hallmark of the Foundations in Science and Mathematics (FSM) program is its graduate-student-led teaching model, which has guided both the recruitment process and the preparation of instructors since the program's inception. Unlike many outreach initiatives that rely primarily on faculty leadership, FSM intentionally places graduate students and advanced undergraduates at the forefront, providing them with the opportunity to design and teach enrichment courses in their fields of expertise. This design accomplishes two goals simultaneously: students in the program are taught by instructors with advanced content knowledge, while graduate students gain valuable hands-on teaching experience that contributes to their professional development.

The recruitment cycle typically begins in early fall. An interest survey is shared widely across STEM departments at Indiana University, inviting potential instructors to indicate both their willingness to teach and the subjects in which they feel qualified. To spark ideas, the FSM website highlights commonly offered courses such as Algebra I, Chemistry, and Python Programming. At the same time, instructors are encouraged to propose new course ideas. When a novel proposal is made, faculty mentors often step in to provide constructive input on course design to ensure feasibility and alignment with the program's goals.

Toward the end of the fall semester, FSM hosts a call-out meeting for interested candidates. This meeting functions as an orientation and a matchmaking step, helping align instructors with courses that suit their academic background. For example, mathematics courses are typically assigned to graduate students in mathematics or mathematics education, while courses in biology, chemistry, or computer science are paired with students from those respective disciplines. If multiple candidates request the same course, priority is given to those with departmental ties, prior teaching experience, or a strong record of engagement in STEM outreach. Returning instructors who have previously taught with FSM are also prioritized; this practice not only strengthens continuity and program stability but also honors the contributions of individuals who have already invested in the program's mission.

Once instructors are selected, FSM implements a structured preparation process during the spring semester. Instructors are grouped by subject areas mathematics, sciences, or computer science and each group is supported by a course administrator. These administrators serve as coordinators, helping to facilitate lesson planning, organize shared resources, and provide logistical guidance. They also play a crucial role in onboarding new instructors by sharing existing instructional materials such as past syllabi, worksheets, manipulatives, and project-based activities. Instructors can adapt these resources or develop entirely new curricula, but all finalized materials are expected to be uploaded to a shared drive to benefit future cohorts of instructors.

Throughout the spring, monthly meetings are held to build community among instructors and provide training. These sessions cover logistical topics (such as scheduling and classroom assignments), pedagogical expectations, IRB and research protocols, classroom management strategies, and available teaching resources. Faculty advisors are accessible to provide additional support, particularly for instructors piloting new courses. Importantly, FSM recognizes that most instructors balance teaching preparation with research and coursework, so the program intentionally cultivates a collaborative, flexible, and supportive environment.

During the summer sessions, instructors receive both logistical and instructional support. Program staff monitor attendance records, maintain a shared spreadsheet that tracks student progress through pre- and post-tests, and act as a point of communication with families. Parents and guardians are encouraged to reach out to the FSM email account with concerns or questions, and relevant feedback is shared with instructors. At the close of each course, anonymous student surveys are collected, providing insights into both teaching effectiveness and student experiences. This ongoing feedback loop strengthens the program's ability to improve from year to year.

The teaching load is designed with sustainability in mind. Most instructors teach one course per session, though some may teach in both of the two summer sessions if needed. In cases where enrollment is small, a second instructor may be assigned to meet supervision requirements and provide classroom support. Additional instructors are occasionally kept on reserve to address illness, scheduling conflicts, or unexpected changes.

Ultimately, FSM's instructor model is grounded in a balance of trust and structured support. Instructors are trusted to design meaningful and engaging learning experiences for their students, while the program ensures that they are equipped with resources, mentorship, and a collaborative peer network. This reciprocal structure has been key to maintaining both the quality of instruction and the enthusiasm of instructors across successive years.

Course Offerings and Curriculum

Each summer, FSM provides a diverse and evolving catalog of STEM enrichment courses. The offerings range from core subjects such as algebra, biology, and chemistry to more specialized options including computer programming, psychology, and SAT preparation. Courses reflect both student interest and instructor expertise, leaving room for creativity and flexibility. While staple courses like Algebra 1 and Python Programming are offered almost every year, others arise from instructor initiative, such as robotics or interdisciplinary courses that connect mathematics with art.

The program is structured into two sessions, usually held in June and July. Courses meet three days a week, Mondays, Wednesdays, and Fridays, for two hours per day over a two-week period, creating a total of 12 hours of instruction. To support pacing, instructors are encouraged to divide each day into two 50-minute blocks separated by a short break, followed by time for questions and reflection. This rhythm helps sustain student focus while balancing direct instruction, collaborative activities, and exploratory work.

Class sizes are intentionally kept small, with enrollment capped at ten students and a minimum of two. Most classes fall between three and six students, which allows instructors to adapt lessons and engage students in interactive ways. If a course enrolls only one student, program policy requires assigning a second instructor to ensure quality. The result is an environment that feels closer to tutoring than to a traditional classroom.

Clear expectations and learning goals are emphasized from the start. Instructors may format these in different ways, but every course begins with a short pre-test and ends with a post-test to measure student growth. Many instructors also integrate projects, group activities, or reflective tasks, particularly in courses like programming, psychology, or the sciences. Courses in biology, chemistry, or environmental science often include laboratory components. The university provides lab space, safety equipment such as goggles and coats, and requires families to sign a safety consent form. Instructors receive logistical and financial support in securing materials, ensuring that lab-based classes are both rigorous and safe.

Technology plays a central role across the curriculum. Classrooms are equipped with projectors and computers, and instructors often use digital platforms like Desmos, GeoGebra, or Python IDEs. These tools enrich lessons whether students are graphing functions, simulating chemical processes, or designing code. The program's technical and material infrastructure is designed to make experimentation and exploration accessible in every subject. Developing a new course typically begins months in advance. Once course descriptions are finalized and advertising begins, instructors work with coordinators and faculty mentors to refine lesson plans, prepare materials, and document their approaches for future use. Whether revising an established course or piloting a new idea, instructors are expected to upload all teaching materials to a shared drive so future teachers can build on their work.

This combination of flexibility, structure, and institutional support allows FSM to offer a wide range of STEM learning experiences while maintaining a consistently high standard of instruction. To illustrate how these offerings come together in practice, Table 1 presents a sample schedule of the 2025 summer courses across both sessions. The courses span mathematics, science, and interdisciplinary topics, with options delivered in both in-person and hybrid formats, reflecting FSM's commitment to accessibility and variety.

Table 1. Sample course schedule from FSM 2025 summer program (both sessions).

Session 1: June 2-June 13, 2025, Monday- Wednesday - Friday			
Time	Course 1	Course 2	Course 3
9:00-11:00	Algebra 2**	Intro Biology*	Intro Physics*
11:30-1:30	Algebra 1*	Pre-Calculus*	Intro Programming*
1:45-3:45	Standardized Test Review**	Psychology and why it matters*	Intro Chemistry*
4:00-6:00	Geometry*	Coding in Python**	Advanced Chemistry*
Session 2: July 7-July 18, 2025, Monday- Wednesday - Friday			
Time	Course 1	Course 2	Course 3
9:00-11:00	Algebra 2**	Viruses and our world*	Brain Science*
11:30-1:30	Algebra 1*	Pre-Calculus*	Intro Chemistry*
1:45-3:45	Standardized Test Review**	Intro Physics*	Coding in Python**
4:00-6:00	Geometry*	Zoology*	Intro to Astronomy*

*Only in person, **Hybrid (online or in person)

Student Recruitment and Enrollment

Recruitment of students for the Foundations in Science and Mathematics (FSM) program begins each spring and is intentionally designed to reach a wide spectrum of learners. Because the program is hosted at Indiana University, many participants come from Bloomington and surrounding counties, yet the program also attracts students from across Indiana and occasionally from neighboring states. The recruitment effort therefore aims to balance two goals: ensuring that local students and families are aware of the opportunities available, and opening the program to a wider audience who may benefit from summer enrichment experiences in STEM.

The outreach strategy has gradually expanded to include multiple channels. Traditionally, recruitment has relied on personal networks and word of mouth, especially through parents of past participants who often share positive experiences with peers. To strengthen these informal efforts, the FSM team also coordinates with local schools, community organizations, and youth programs. Information flyers and digital announcements are distributed through school mailing lists, while teachers and counselors are encouraged to nominate students who may thrive in enrichment settings. In recent years, social media platforms and targeted email campaigns have become increasingly important in widening the program's visibility. These efforts ensure that recruitment is not limited to families already familiar with Indiana University, but instead reaches a diverse pool of potential participants.

Enrollment officially opens each year on March 1 through an online registration system hosted by the university. Families can review the available course offerings, session dates, and times before selecting the courses that best align with their child's interests and schedules. Because courses often fill quickly, early registration is encouraged. The administrative team tracks enrollment numbers carefully and maintains waitlists for high-demand courses, notifying families if additional seats become available. The enrollment system also collects demographic data, prior coursework, and areas of interest, which helps instructors tailor their courses to the needs and backgrounds of incoming students.

Equity and accessibility remain central concerns throughout this process. The program strives to keep tuition costs affordable while also providing fee waivers or reduced rates for families with demonstrated financial need. In addition, courses are scheduled with flexibility in mind, offering both morning and afternoon sessions so that families can select times that do not conflict with other summer commitments. Together, these efforts underscore FSM's dual mission: to expand access to high-quality STEM learning opportunities and to maintain a supportive, inclusive community of learners each summer.

Scheduling and Facilities

Over time, FSM has established a summer schedule that is both predictable and flexible, making planning smoother for instructors, students, and families. Each year, the program runs in two sessions: the first begins on the first Monday in June, and the second starts on the second Monday in July. This structure has remained steady for more than a decade, and its consistency has been key for returning families, who are able to plan their summers in advance, and for instructors, who can reliably anticipate when their teaching responsibilities will occur.

Each session spans two weeks, with courses meeting three times per week on Mondays, Wednesdays, and Fridays for two hours per day. This format balances intensity and manageability: students complete a full 12 hours of instruction in two weeks, while instructors have non-teaching days in between to revise materials, prepare new lessons, and follow up with students. The rhythm of the schedule has become one of FSM's strongest features, accommodating a variety of summer calendars while maintaining a meaningful depth of learning.

Classes are held in multiple buildings on the Indiana University campus, including Ballantine Hall, the Chemistry Building, and the Biology Building. These facilities were chosen for their proximity to one another, which simplifies navigation for families, and for the specialized resources they offer. Laboratory courses such as biology and chemistry are scheduled in university labs that meet safety requirements, while programming and SAT preparation courses take place in classrooms with projectors, computers, and reliable internet access. The program coordinator, a graduate student, typically manages the process of reserving rooms, though faculty advisors and departmental staff assist with navigating IU's scheduling system and coordinating with science departments. Over time, FSM has developed strong relationships with these units, ensuring that classroom and lab space is consistently available each summer.

On the first day of each session, a registration desk is set up in the main building to welcome families, guide students to classrooms, and collect any final documentation. This desk is staffed by coordinators and instructors from morning until evening and serves as the central hub for communication. It may seem like a small detail, but this welcoming point has been crucial in setting the approachable and supportive tone that families have come to associate with FSM.

Because FSM is also a research initiative, instructors are required to complete certain compliance trainings. All instructors are added to the program's IRB protocol, since pre- and post-test data, along with student surveys, are used for evaluation and research purposes. Those who have not already completed CITI (Collaborative Institutional Training Initiative) training must do so before the summer begins. For laboratory-based courses, instructors must also complete safety training if they have not already done so through their home departments. FSM provides all the necessary lab materials and protective gear such as goggles, gloves, and lab coats and strictly follows IU's established safety procedures. These layers of preparation ensure that classes are not only engaging, but also safe and research compliant.

Importantly, FSM has not struggled to secure facilities. The scale of Indiana University's campus, combined with the relative flexibility of summer scheduling, has made it possible to find appropriate spaces even as the number of courses has grown. Proactive planning by the leadership team, coupled with strong departmental partnerships, has kept operations smooth and reliable year after year.

To highlight how this planning unfolds across the academic year, Figure 1 presents the FSM Program Timeline, a month-by-month overview of major milestones such as instructor recruitment, course scheduling, student enrollment, and the summer sessions themselves. The timeline illustrates how work begins long before June, starting with an early interest survey in September and moving step by step through call-out meetings, finalizing instructors, planning courses, and coordinating outreach. By the spring semester, attention shifts to logistics such as scheduling classrooms, opening registration, and preparing instructors through course-specific meetings. May is devoted to final confirmations, including reviewing enrollments, reserving facilities, and making public announcements. Finally, in the weeks just before the program launches, the team finalizes course rosters and makes adjustments as needed, ensuring that only viable courses move forward.

This cycle shows that FSM is not just a summer project but a year-round commitment that requires foresight, organization, and collaboration. The visual highlights the cyclical nature of the program, where each stage builds on the previous one and lessons learned from one summer inform the planning of the next. By the time students arrive in June and July, months of coordinated effort have already taken place, making it possible for the sessions to run smoothly. The figure underscores how the program's sustainability depends on this structured yet flexible planning process, with graduate students, administrators, and faculty advisors all contributing to the momentum that carries FSM from year to year.

Taken together, these steps highlight the careful planning and coordination required to sustain FSM year after year, and they set the stage for the pedagogical approaches described in the next section.

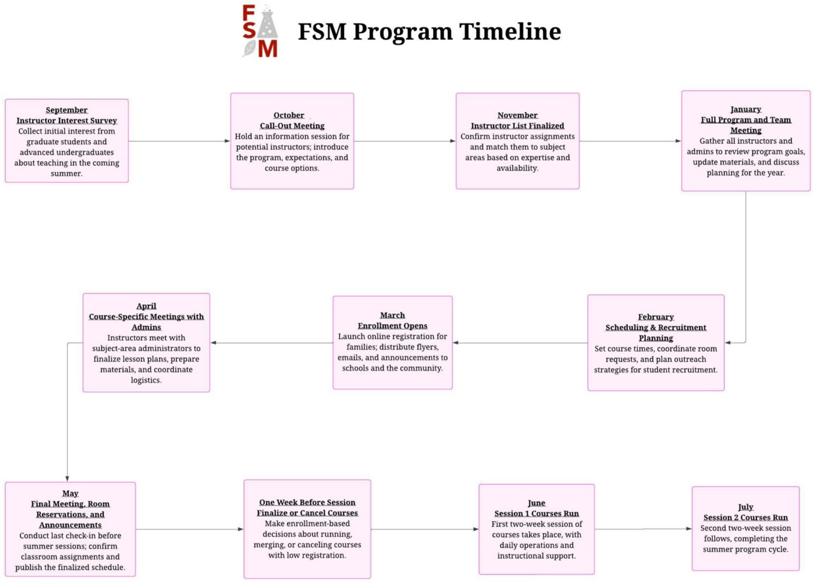

Figure 1. FSM Program Annually Timeline

Pedagogical Approaches

Instructional design in FSM is rooted in the belief that students learn best when they are active participants in the learning process. Rather than accelerating curriculum coverage or rushing through content, FSM seeks to create opportunities for students to explore STEM concepts in meaningful, low-pressure settings. The focus is on fostering curiosity, building confidence, and giving students the freedom to ask questions and pursue ideas. This orientation reflects broader shifts in STEM education, which increasingly emphasize inquiry, exploration, and identity development as central to effective teaching and learning (Fosnot, 2013; Windschitl, 2002).

The design of FSM courses is grounded in constructivist learning theory. Students are encouraged to build new understandings by connecting fresh ideas to what they already know, and by engaging in dialogue and collaborative activities with peers (Piaget, 1950; Vygotsky, 1978). Inquiry-based instruction is a central strategy in this regard, as it allows learners to investigate problems, gather evidence, and develop their own explanations. Such approaches have long been shown to be especially effective in STEM contexts, where active problem-solving and authentic application of knowledge are critical (National Research Council [NRC], 2000; Crawford, 2000).

One feature that sets FSM apart is its instructor base. Each summer, courses are taught primarily by PhD students and advanced graduate students in STEM or STEM education. These instructors bring both strong disciplinary knowledge and formal pedagogical training to their classrooms. Their teaching often reflects the principles of Pedagogical Content Knowledge (PCK) (Shulman, 1986), which emphasizes the ability to present subject matter in ways that make it accessible and engaging to diverse learners. Many also integrate digital tools through the framework of Technological Pedagogical Content Knowledge (TPACK) (Mishra & Koehler, 2006), making use of platforms such as Desmos, GeoGebra, and digital simulations to enhance visualization, interactivity, and student participation.

Preparation for teaching is taken seriously. While FSM does not require formal lesson plan submissions, instructors are expected to prepare a sequence of 12 instructional hours across the two-week session. These plans typically combine a mix of whole-class discussions, guided inquiry tasks, independent practice, and hands-on activities. To support this work, course administrators provide access to a shared archive of past syllabi, worksheets, projects, and lesson outlines. New instructors often adapt these resources, while returning instructors update and refine materials based on their previous experiences. Planning usually begins several months in advance, with mentoring and collaboration available from course administrators and faculty advisors.

A hallmark of FSM instruction is its intentionally low-stakes environment. Each course includes a pre-test and post-test, but these assessments are used only for program evaluation, never for ranking or grading students. The results give instructors insight into students' prior knowledge and growth, while also serving as feedback for the program as a whole. This approach aligns with formative assessment principles (Black & Wiliam, 1998), which emphasize learning progress over performance outcomes. It helps students view assessments as tools for growth rather than as sources of stress, and it allows instructors to adapt their teaching in real time to meet student needs.

Small class sizes usually three to six students further support individualized instruction. With such groups, instructors are able to build strong relationships with their students, tailoring explanations, pacing, and activities to the interests and levels of each learner. A typical class period might be divided into two 50-minute sessions with a short break in between, and instructors often end the day with an open Q&A or reflection period.

These closing moments provide students with space to voice lingering questions and to consolidate their learning in conversation with peers and instructors.

While FSM courses do not require capstone projects or final presentations, many instructors incorporate group-based investigations, lab work, or mini-projects. For example, computer programming students might present a simple app or game they designed, while biology students may share results from a lab experiment. Courses that involve labs, such as chemistry and biology, are supported with appropriate facilities, equipment, and safety protocols, ensuring that students have authentic exposure to scientific practices. The integration of digital and physical manipulatives also allows students to engage STEM concepts through multiple modalities.

Collaboration and professional community are also key features of FSM pedagogy. Instructors are encouraged to visit one another's classes, exchange ideas, and share resources. Course administrators often facilitate this cross-pollination by organizing informal check-ins and by making sure instructors have access to a common pool of teaching materials. This culture of openness allows instructors to learn from each other's successes and challenges, and it fosters a sense of belonging within the program.

Ultimately, FSM's pedagogical approach reflects a commitment to accessible, research-informed instruction that remains flexible and responsive to the needs of students and instructors alike. By centering active learning, inquiry, and community, FSM creates a model of summer STEM education that is not only academically rigorous but also deeply human one that cultivates intellectual growth while nurturing enthusiasm and confidence in the learners who participate.

Leadership and Coordination

One of FSM's distinguishing features is that, while it serves middle- and high-school students, it is coordinated end-to-end by graduate students from STEM and STEM-education fields. This graduate-student–led arrangement has underpinned the program's longevity: it creates authentic leadership roles planning the schedule, matching instructors to courses, communicating with families, and coordinating with departments while keeping curriculum and instruction anchored in current disciplinary knowledge and sound pedagogy. In practice, the model gives emerging scholars real responsibility and keeps the program nimble, responsive, and academically rigorous.

A Distributed Leadership Model

Each year, FSM is directed by at least one graduate student who serves as the Lead Coordinator. In some years, this individual is joined by a co-lead or a trainee coordinator who shadows the role in preparation for future leadership. The Lead Coordinator oversees the full scope of program operations from selecting instructors and finalizing course schedules to communicating with families and managing day to day logistics.

Supporting this role are Course Administrators, also graduate students, who specialize in specific content areas such as mathematics, science, or computer science. These course admins act as the primary point of contact for instructors in their discipline, helping to manage teaching materials, mentor less experienced instructors, and troubleshoot scheduling or organizational concerns.

Alongside graduate leadership, faculty advisors play a crucial but deliberately background role. They provide institutional oversight and ensure continuity, particularly by managing the program's budget, assisting with grant proposals, and preparing annual reports for sponsors. Faculty also maintain cross-campus partnerships and confirm that FSM adheres to university policies and safety requirements.

Program funding fluctuates from year to year and is drawn from a mix of sources, including the university, academic departments, and external grants (e.g., NASA and the Indiana Space Grant Consortium). Graduate student instructors are not directly involved in financial management. Instead, the Lead Coordinator submits updated rosters and course data, while faculty and departmental staff handle the administrative processing of stipends and reimbursements.

Planning Timeline and Instructor Coordination

Planning for the next summer begins almost immediately after the previous program ends. Once Session 2 concludes in July, the leadership team starts considering who might assume the coordinator role for the following year. Ideally, a successor is identified early so that they can shadow the current lead throughout the academic year, gradually learning the responsibilities and processes involved in running the program.

During the fall semester, FSM circulates an Instructor Interest Survey to graduate students in STEM-related departments as well as to past instructors. The survey collects details about subject expertise, availability, and potential course topics, providing an initial pool of candidates. Toward the end of the semester, the program hosts a call-out meeting where interested instructors are welcomed, program goals and expectations are explained, and logistical details are shared. This meeting also serves as an early step in aligning prospective instructors with possible courses.

When there is more than one applicant for a course, preference is typically given to those with relevant teaching experience or strong departmental ties. Returning instructors are also prioritized, both to recognize their contributions and to preserve continuity in instructional quality. New instructors, by contrast, may initially be placed in a reserve pool to serve as secondary teachers or as backups in case of scheduling conflicts or unexpected absences. This system has proven valuable for maintaining flexibility while ensuring that every class has adequate coverage.

By the start of spring, the roster of instructors is finalized, and specific course assignments are confirmed. Monthly meetings begin at this stage, giving instructors the chance to collaborate on course preparation, clarify program expectations, and coordinate outreach efforts. These meetings also provide a venue for experienced instructors and course administrators to share strategies, lesson materials, and insights from previous summers helping to build continuity while also allowing for innovation.

Coordinating Daily Operations

The smooth operation of FSM during the summer sessions is the result of both careful advance planning and strong, ongoing communication among all participants. Each session begins with a registration day, during which instructors staff a welcome desk in the program's main building. Here, families are greeted in person, consent forms are collected, and students are guided to their classrooms. This initial point of contact not only sets a professional and organized tone for the program but also reassures families that their children are entering a safe and supportive learning environment.

Throughout the summer, the lead coordinator is physically present on-site to address any emerging issues as they arise. Whether the concern involves classroom access, a student's unexpected absence, technical challenges, or a last-minute scheduling adjustment, the coordinator provides a reliable point of leadership and support. Day-to-day communication between instructors and the lead team takes place through multiple channels including email, in-person conversations, phone calls, or text messages ensuring that no issue is left unresolved for long.

Collaboration among instructors is also actively encouraged. In cases where a course has only one registered student, a second instructor is assigned to satisfy university supervision requirements. In these situations, the second instructor often contributes as a collaborator or observer, which not only maintains compliance but also provides the student with a richer educational experience. Course administrators, who oversee the broader subject areas of math, science, and computer science, check in regularly with instructors to offer pedagogical advice, provide additional teaching resources, and troubleshoot logistical challenges.

Together, this layered structure of coordinators, course admins, and instructors ensures that daily operations are both flexible and reliable. The emphasis on open communication and shared responsibility reflects FSM's broader philosophy: the program thrives not only because of individual contributions but also because of the collective support and collaboration among its teaching community.

External Communication and Institutional Support

Clear and consistent communication with families and university partners is essential to FSM's success. To streamline this process, the program maintains a dedicated email account, monitored daily by the lead coordinator during the summer months. All official inquiries from parents, students, or university staff are funneled through this account to ensure timely and accurate responses. Families typically receive a welcome email both from the program and from their child's instructor before the session begins. These messages include practical details such as classroom locations, daily schedules, contact information, and any required forms. Once classes are underway, instructors serve as the first point of contact for families regarding student progress or classroom concerns, while the coordinator remains available for broader logistical or administrative issues.

On the institutional side, FSM collaborates closely with several units across Indiana University. IU Conferences provides vital support for handling registrations, billing, and financial records, while departments such as Physics, Chemistry, and Biology help secure access to laboratories, specialized equipment, and technical resources. Faculty staff are often instrumental in coordinating these arrangements, particularly when purchases need to be made with external grant funding or when reporting requirements must be met. To avoid scheduling conflicts, space reservations are submitted at least one month in advance, and strong relationships with campus departments have helped FSM consistently secure the classrooms and labs it needs.

The program's collaborative leadership model ensures that these responsibilities are distributed effectively. Lead coordinators oversee the flow of information, course administrators address subject-specific needs, faculty advisors safeguard compliance and budgetary oversight, and instructors maintain direct lines of communication with students and families. Through this division of labor, graduate students gain experience not only in course design and teaching but also in program administration, financial coordination, and institutional partnership-building. These skills extend well beyond the scope of FSM and prepare participants for future roles in academic leadership, educational program management, and community engagement. In this way, FSM's external communication and institutional support structures do more than keep the program running smoothly they also model the kind of professional collaboration and organizational transparency that graduate students will encounter in their careers.

Reflections from Program Leaders and Instructors

Lead Author Reflection

My journey with the Foundations in Science and Mathematics (FSM) program began in Spring 2021, during the first year of my PhD studies. A colleague who served as the mathematics course administrator invited me to consider teaching in the summer program. With five years of experience as a high school mathematics and geometry teacher in Türkiye, I was drawn to FSM's goal of increasing high school students' interest in STEM. I applied and was assigned to teach the Standardized Test Review course, commonly referred to as SAT Preparation. That summer marked the beginning of my enduring relationship with FSM.

For the first two years (2021–2022), I participated as an instructor. In 2023, I transitioned into a leadership role as the mathematics course administrator. This role involved coordinating math instructors, facilitating communication, and managing course-related logistics. Thanks to this responsibility, I worked more closely with the FSM coordinator, and as they prepared to graduate, I was invited to shadow them. I served as co-coordinator in 2023 and took on full coordination responsibilities in 2024. I continue to serve as the FSM coordinator in 2025, and I will mentor the incoming coordinator next year before graduating.

My instructional experience in FSM reflects my desire to teach a range of math courses. I taught Standardized Test Review, Algebra 1, Geometry, and Precalculus, adjusting and enhancing the curriculum each year. My instructional goals have included increasing student engagement through technology (e.g., Desmos, GeoGebra), adapting problem-solving strategies from my experiences in Türkiye, and helping students build mathematical confidence. My prior work with test preparation centers and textbook writing in Türkiye also shaped my approach to SAT strategies. FSM provided an opportunity to refine these practices, and I incorporated self-study elements to document my growth as both a teacher and a researcher.

FSM has also allowed me to appreciate the unique challenges of teaching students from diverse grade levels (e.g., both 7th and 9th graders in an Algebra 1 class), requiring differentiated strategies. Unlike undergraduate teaching at the university, FSM offered real-time classroom experiences with younger learners and supported my understanding of the U.S. secondary curriculum. Teaching in a culturally and linguistically diverse environment also enriched my teaching and allowed me to promote equity in the classroom.

As a leader, FSM helped me grow in several ways. While I had prior leadership experience in student organizations and conferences, FSM allowed me to lead within an instructional context working with instructors, faculty, families, and students. I learned how to coordinate with university faculty, manage program logistics, and mentor new instructors. I also strengthened my communication skills with local teachers and school administrators, especially during outreach and recruitment.

One challenging moment was building the teaching schedule. Balancing instructor availability with student needs and course offerings was not always easy. I realized that being a leader meant making decisions that might not please everyone but ultimately served the program's goals and ensured fairness. Another challenge involved supporting students who struggled with payments. Initially unsure of the protocol, I learned that FSM prioritized accessibility over revenue and was empowered to grant scholarships. These moments deepened my sense of responsibility and trust in collaborative decision-making.

I found that clear task delegation and shared responsibilities fostered a strong team dynamic. Many of our instructors were PhD students like myself, and our mutual respect allowed us to collaborate effectively. I made a conscious effort to be approachable and present responding to emails, attending sessions, and contributing alongside others. Rather than directing from above, I worked alongside the team. This collaborative leadership style helped sustain a sense of shared ownership and motivation.

FSM significantly shaped my professional identity. The program complemented my doctoral coursework and research by providing a hands-on teaching and leadership platform. I believe FSM has helped me become a more reflective educator and a more empathetic leader. It strengthened my understanding of high school curricula in the U.S., particularly in comparison with my background in the Turkish education system.

Looking ahead, I aim to adapt FSM-style enrichment programs in Türkiye and beyond. STEM education is gaining importance globally, and summer programs like FSM can be powerful tools for outreach and innovation. With support from universities and local schools, and by incorporating technological tools such as Desmos and GeoGebra, we can create engaging, research-based summer learning environments. These programs can serve both students and teachers providing professional development and student learning opportunities simultaneously.

FSM taught me that good leadership involves balance: making fair, informed decisions even when they are difficult, and maintaining open communication. For new PhD students, I would strongly recommend FSM for several reasons: it allows you to apply your theoretical learning, improve your teaching skills, contribute meaningfully to high school students' education, build professional networks, develop leadership, and participate in a collaborative, research-oriented community. FSM is not just a summer job, it's a learning lab, a leadership incubator, and a space for meaningful connection.

Co-author Reflection

My journey as an instructor of FSM program began in the summer 2022, following a recommendation from senior colleagues in my Mathematics Education PhD program at Indiana University Bloomington. Prior to joining the program, I taught mathematics to middle and high school students in South Korea and Ethiopia for approximately four years. Wanting to build on this prior experience, I sought opportunities to teach secondary-level mathematics in the U.S. Fortunately, the FSM summer courses provided a valuable setting where I could engage with middle and high school students in a classroom environment. From 2022 to 2024, I taught precalculus and SAT preparation courses over three summers.

For SAT preparation course, I selected a textbook after reviewing several options from the library. I chose one that offered concise content reviews and a wide range of problems categorized by topic. I focused on key topics such as algebraic expressions, geometry, probability and statistics, devoting one topic per day. I aimed to have a balance between practicing problem-solving and understanding why math rules work. For instance, during the geometry unit, I included an activity where students explored why the sum of interior angles of a triangle is 180 degrees. Before the activity, I asked students what the sum was everyone responded with 180, but no one could explain why. To deepen their understanding, I provided various types of triangles labeled by name. Students cut out the triangles and arranged the pieces on a separate sheet of paper to see that the angles formed a straight line, demonstrating that their sum is 180 degrees. This hands-on activity helped students not only understand a well-known geometric fact but also review different types of triangles and their characteristics. I believe that the meaningful mathematical learning happens when students connect procedural knowledge or memorized facts to conceptual understanding.

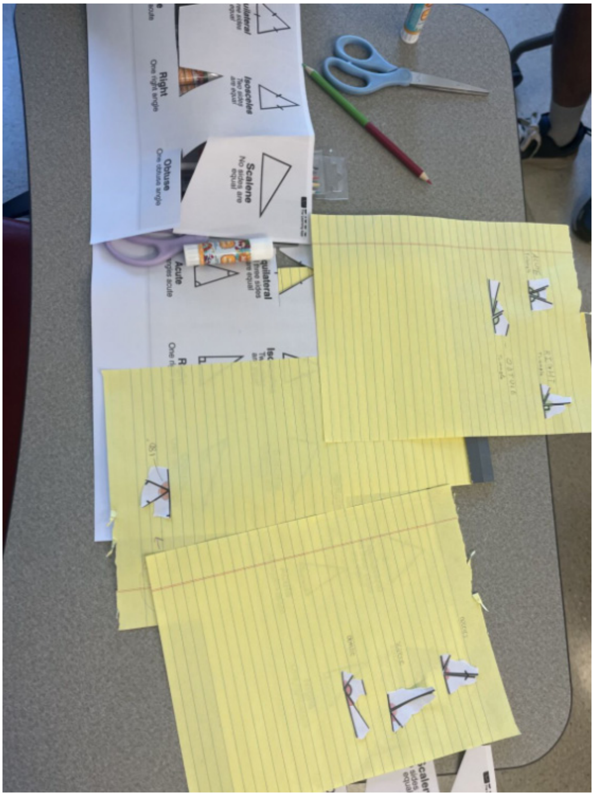

Figure 2. Geometry activity to prove the sum of interior angles of a triangle is 180 degrees

For precalculus courses, one instructional approach I would like to highlight is my active use of GeoGebra. In particular, I used it to support students' understanding of trigonometric functions. For example, when introducing transformations of the sine function, we explored how changed in an equation affect the graph. I asked students to compare various functions of by changing numbers of A, B, C, and D, focusing on identifying the amplitude and period. They could sketch the graph on their grid paper and then checked their graph by inserting the equations to GeoGebra. I also encouraged them to explain the role of the coefficient B in the equation. Through this visual and interactive activity, students were able to make meaningful connections between the algebraic form of the function and its graphical representation.

Additionally, I incorporated more student-led activities during class. One example was having students solve the same math problem by themselves on the blackboard in pairs, using chalk, and then present their solutions to the class. This structure allowed students not only to articulate their mathematical thinking through explanation but also to learn alternative problem-solving strategies by engaging with their peers' approaches.

As a common classroom context, there were various level of students in mathematics joined the same class. Sometimes, there were different grade level students joined the same course. To support all students according to their prior knowledge and mathematical background, I made it a priority to identify those students who needed additional help as well as those who were ready for more advanced challenges.

Pre-tests and pre-surveys played a crucial role in identifying students' backgrounds and levels in math. Administered on the first day of class, they included problems aligned with the course topics and helped me gauge each student's mathematical readiness. The textbook I selected also supported differentiation as it included problems at various levels of difficulty. I assigned foundational problems for all students and reserved more challenging problems for those who demonstrated advanced understanding. When advanced students completed the basic problems quickly, I provided them with additional tasks to deepen their learning. Furthermore, I encouraged students to explain their mathematical reasoning to one another. This peer interaction helped refine their thinking and provided opportunities to extend their understanding through collaborative learning.

Overall, my experiences teaching in the FSM program over the past three summers have been meaningful and formative. They allowed me to bridge my prior teaching experience with new instructional strategies that support diverse learners in the U.S. classroom context. Through thoughtful lesson planning, use of technological tools like GeoGebra, and differentiated instruction based on students' needs, I have grown in my ability to foster conceptual understanding and student engagement in mathematics. These teaching opportunities have strengthened my commitment to student-centered teaching practices, which I will continue to carry forward in my future work as a mathematics educator.

Implications and Future Directions

The Foundations in Science and Mathematics (FSM) program offers several unique contributions to STEM education that distinguish it from other summer enrichment programs. One of the most significant features of FSM is its instructional model, which centers around graduate student instructors, many of whom are doctoral students actively engaged in research in mathematics, science, or computer science education. These instructors bring cutting-edge disciplinary knowledge and pedagogical innovation into the classroom, delivering instruction that is both aligned with high school curricula and enriched by advanced academic perspectives.

FSM courses are carefully designed to balance the academic goals of reinforcing school content and introducing students to novel strategies and tools. For example, geometry instruction often incorporates digital tools such as Desmos and GeoGebra, which enable visualizations and interactions beyond what is possible in traditional settings. These tools not only help deepen students' conceptual understanding but also reflect the instructors' own research-based pedagogical development.

Equity and innovation are also key pillars of FSM's approach. The program is open to all students regardless of race, gender, or socioeconomic background, and instructors strive to adapt lessons to meet the varying needs and prior knowledge levels of participants. Pre-tests, in-class observations, and formative assessments help instructors provide more tailored instruction within the program's short two-week window. Innovation also stems from the instructors' roles as teacher educators and researchers, allowing them to implement and experiment with new instructional strategies that reflect current trends in STEM pedagogy.

The FSM model also offers transferable practices that could inform similar programs elsewhere. Its structure, which has been sustained over 15 years, could serve as a replicable model for short-term STEM camps focused on specific disciplines like math, science, or computer science. The dual-session summer schedule (June and July) gives families flexibility and allows some students to return for a second course. FSM's hybrid model developed during the COVID-19 pandemic further increased accessibility, particularly for courses where online delivery is feasible and effective, such as mathematics or programming.

Some of the most adaptable features of FSM include its use of doctoral students as instructors, the provision of university classroom spaces to introduce high school students to college environments, and a commitment to accessibility through financial support and scholarships. FSM's student-centered pedagogy, which emphasizes discovery and exploration, is consistent with contemporary educational values and can be extended to diverse settings.

Looking ahead, the future vision for FSM includes the continued offering of core STEM courses while integrating emerging topics. Recent additions such as Coding in Python and Viruses in Our World exemplify how the program responds to students' evolving interests and global developments. Future expansions may include topics like artificial intelligence and data science, as instructors bring their specialized knowledge to bear on course design.

FSM's structural and pedagogical development continues to evolve. The program encourages instructors to refine and personalize their lesson plans while drawing on shared curricular resources. Graduate instructors who are experts in their fields enrich the teaching and learning experience with their advanced content knowledge and ongoing research.

FSM has also had a significant impact on the professional development of its instructors. For many, the program serves as a laboratory for applying and reflecting teaching strategies, including those focused on student engagement, equity, and the integration of technology. Leadership roles, whether as course administrators or coordinators, further develop organizational and communication skills essential for future academic careers.

From a research standpoint, FSM provides fertile ground for educational inquiry. As a site for ongoing data collection through surveys, pre- and post-tests, and interviews, the program supports studies on students' STEM interests, instructional effectiveness, and program impact. Direct interaction with students and families also helps overcome challenges commonly faced by graduate student researchers in recruiting participants for studies. For example, instructors have used FSM as a site for self-study using frameworks like Mathematical Quality of Instruction, or for piloting methods they will later use in preservice teacher education.

In sum, FSM represents a vibrant, evolving model of summer STEM enrichment that blends academic rigor, equitable access, and pedagogical innovation. Its long-term sustainability and adaptability make it a compelling blueprint for similar initiatives in other local, national, or international contexts.

Conclusion

The Foundations in Science and Mathematics (FSM) summer program at Indiana University exemplifies what a sustainable, student-led STEM outreach initiative can accomplish when built on collaboration, intentional design, and reflective leadership. Over its 15-year history, FSM has served as a bridge between university resources and local middle and high school students, offering them a glimpse into the academic world of science, technology, engineering, and mathematics in an accessible and enriching way. At its core, FSM has generated significant educational benefits for all involved. Students are introduced to graduate-level STEM instructors and university settings in a low-stakes environment that fosters curiosity rather than anxiety. Free from the pressures of grades or exams, participants gain early exposure to advanced content and new pedagogical approaches, which often reshapes their attitudes toward learning and their aspirations for higher education. These encounters with doctoral-level educators, many of whom bring global perspectives as international students broaden students' understanding of what STEM can look like and who it is for. FSM has also offered invaluable professional development for instructors. For many graduate students, FSM is their first opportunity to independently design and teach a course, implement instructional strategies, and engage with youth in a sustained educational setting. Teaching middle and high school learners allows instructors to apply theoretical knowledge in real time and reflect on their practice. These experiences not only contribute to their development as educators and researchers but also cultivate leadership and organizational skills critical for future academic and administrative roles. The program's longevity is no coincidence. FSM's sustainability has been driven by a continuous mentorship model in which outgoing leaders train their successors, strong university support, dedicated instructors who believe in the mission, and families who return year after year. Access to small grants and institutional partnerships has also been key to supporting instructors financially and ensuring that the program remains affordable or free for students. This coordinated effort between university departments, graduate students, schools, and families has ensured that FSM remains deeply rooted in the local community while also scalable and adaptable. From a research perspective, FSM offers a unique environment for studying STEM education practices in action. Its flexible structure allows instructors to pilot innovative teaching methods, gather data, and reflect using various theoretical frameworks, such as self-study or the Mathematical Quality of Instruction (MQI) framework. The ease of reaching diverse student populations, including those underrepresented in STEM, makes FSM a rich site for exploring student engagement, learning outcomes, and pedagogical design. Several studies have already used FSM as a research context, and future opportunities especially those integrating qualitative interviews, observations, and new assessment frameworks are abundant. Looking forward, FSM holds promise not only as a continued summer enrichment program but also as a model for other institutions and regions. With appropriate institutional backing, similar programs could be adapted in universities across the world, including in Türkiye, where graduate students and faculty could build community-engaged outreach aligned with national STEM education goals. The hybrid format has increased reach, but instructors continue to advocate for face-to-face formats for certain courses particularly those requiring hands-on lab or fieldwork experiences. Ultimately, FSM serves as a reminder that STEM education reform does not solely depend on large-scale policy shifts. It can begin with a group of committed educators, a supportive institutional environment, and a shared vision for equity and engagement. The FSM model is not merely about delivering content it's about building relationships, encouraging exploration, and shaping future educators and learners. Programs like FSM create space for collaborative, generative work that benefits all stakeholders and that, perhaps, is its most enduring contribution.

References

Alexander, K. L., Entwisle, D. R., & Olson, L. S. (2007). Summer learning and its implications: Insights from the Beginning School Study. New Directions for Youth Development, 2007(114), 11–32. https://doi.org/10.1002/yd.210

Black, P., & Wiliam, D. (1998). Assessment and classroom learning. Assessment in Education: Principles, Policy & Practice, 5(1), 7–74.

Cooper, H., Nye, B., Charlton, K., Lindsay, J., & Greathouse, S. (1996). The effects of summer vacation on achievement test scores: A narrative and meta-analytic review. Review of Educational Research, 66(3), 227–268. https://doi.org/10.3102/00346543066003227

Crawford, B. A. (2000). Embracing the essence of inquiry: New roles for science teachers. Journal of Research in Science Teaching, 37(9), 916–937.

Davis, K. E. B., & Hardin, S. E. (2013). Making STEM fun: How to organize a STEM camp. Teaching Exceptional Children, 45(4), 60–67. https://doi.org/10.1177/004005991304500406

Drey, L. E. (2016). Effects of STEM summer camp on motivation and interest in mathematics and science (Doctoral dissertation). University of Southern Mississippi. ProQuest Dissertations Publishing.

Fosnot, C. T. (2013). Constructivism: Theory, perspectives, and practice (2nd ed.). Teachers College Press.

Franks, B. A., & McGlamery, S. L. (2021). Effects of teaching in a summer STEM camp on the mathematics teaching self-efficacy of highly qualified preservice secondary mathematics teachers. Metropolitan Universities, 32(2), 45–67. https://doi.org/10.18060/24166

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. Teachers College Record, 108(6), 1017–1054.

National Research Council. (2000). Inquiry and the national science education standards: A guide for teaching and learning. National Academies Press.

National Research Council. (2012). A framework for K–12 science education: Practices, crosscutting concepts, and core ideas. National Academies Press.

Piaget, J. (1950). The psychology of intelligence. Routledge.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. Educational Researcher, 15(2), 4–14.

Tekbıyık, A., Baran Bulut, D., & Sandalcı, Y. (2022). Effects of a summer robotics camp on students' STEM career interest and knowledge structure. Journal of Pedagogical Research, 6(2), 162–178. https://doi.org/10.33902/JPR.202215959

Vygotsky, L. S. (1978). Mind in society: The development of higher psychological processes. Harvard University Press.

Windschitl, M. (2002). Framing constructivism in practice as the negotiation of dilemmas: An analysis of the conceptual, pedagogical, cultural, and political challenges facing teachers. Review of Educational Research, 72(2), 131–175.

Young, J., Ortiz, N., & Young, J. (2017). STEMulating interest: A meta-analysis of the effects of out-of-school time on student STEM interest. International Journal of Education in Mathematics, Science and Technology, 5(1), 62–74. https://doi.org/10.18404/ijemst.61149

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From Curiosity to Discovery: Promoting Student STEM Research in Rural High Schools

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Chapter Highlights

This chapter examines how authentic STEM research experiences can be designed and sustained to support rural high school students through targeted mentoring, place-based learning, and community partnerships.

- Rural STEM Challenges: Rural students face persistent barriers such as limited access to advanced STEM courses, mentors, technology, and funding, which restrict participation in high-quality STEM research.
- NC STEM Research Academy Model: The chapter introduces the NC STEM Research Academy as a scalable framework to increase rural student participation in STEM research and engineering design.
- Teacher-Led Mentorship: Rural teachers are positioned as key facilitators, with professional development, stipends, and sustained support strengthening teacher–student research partnerships.
- Place-Based & Funds of Knowledge: Student projects are grounded in local community needs, place-based contexts, and family knowledge, enabling meaningful and resource-efficient research.
- Flexible & Virtual Mentoring: The use of virtual mentoring, near-peer support, and local materials helps overcome geographic isolation and infrastructure limitations.

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Introduction

Conducting STEM research is useful for all students but an especially valuable one for rural high school students. According to Why Rural Matters (2023) there are over 7 million students enrolled in rural school districts representing 15.7% of all public-school students in the United States and one in seven of these live below the poverty line. Rural students have many challenges that may hinder their academic success, growth and opportunities in STEM. These challenges can include limited access to advanced STEM courses in math, science, engineering, and computer science, fewer teachers qualified to teach in STEM content areas, limited access to technology, fewer extracurricular programs in STEM, fewer community-STEM based resources, and less financial support (Why Rural Matters, 2023; De Mars et al., 2022; Grimes et al., 2019; Marksbury, 2017). Finally, in many rural districts one third or more of students do not have internet connectivity at home (National Center for Education Statistics, 2023). These limitations restrict high school students' access to high-quality STEM education and workforce development in rural areas. By engaging in STEM research, students can access local resources, mentors, and experiences that might otherwise be overlooked in rural areas. Performing STEM research gives rural students the opportunity to build essential skills, foster critical thinking, strengthen academic confidence, and helps them to consider access to high-demand jobs and higher education.

Why a NC STEM Research Academy?

According to Public Schools First NC (2025), more than one in three students attend school in a rural district and North Carolina has the second largest rural student population in the US, after Texas. Eighty of North Carolina's 100 counties are predominately rural and 42 percent of schools in the state are rural. North Carolina is one of the US states where rural students graduate high school at a lower rate than their non-rural peers. The challenge for engaging rural high school students in STEM research is two-fold. First, students must be convinced the effort is worthwhile and second, students must be provided with the resources and encouragement to succeed. Our project partners established a high school NC STEM Research Academy to increase the pipeline of diverse students engaged in STEM research in rural school districts in eastern and western NC. We have worked together for many years and came to realize that a large percentage of students were not being introduced to STEM research in high school. Facilitating high quality student research is a challenge in rural areas with limited access to community resources, materials and mentors.

Originally, we conceived the idea of a NC STEM Research Academy to develop grant proposals to state and federal agencies with a long history of supporting K-12 STEM research competitions in NC. With over 15 years of experience, we saw the same set of high school students with STEM research projects often competed against each other at the yearly events.

These students were typically not ethnically diverse and, for the most part, came from the same schools, geographically located in the same major urban areas of the state. In order to diversify and increase the number of students from across North Carolina, the Academy partners targeted schools located in the coastal, eastern part of North Carolina and the mountains, western area of North Carolina. Both areas are classified rural and have high poverty populations.

Because of the project partner experience in working with NC rural teachers and students, we knew from the outset the following program parameters:

1. The key to working with students is identifying and working with a teacher who will in turn support the student.
2. Rural teachers who are willing to work with students conducting STEM research typically have little to no experience with research themselves.
3. Most rural students are new to research and have little to no experience with either the scientific method or engineering design process.
4. Student STEM research is not explicitly listed in the state science or math standards, and so student work needs to be completed during extra-curricular hours.
5. There are fewer resources, financial, STEM mentors, STEM businesses, etc. available to students in rural areas.

Given these conditions, we designed the NC STEM Research Academy. The program began in 2017 with more than fifty students, and ten teachers total from eastern and western North Carolina. The project partners included university STEM outreach education specialists from two universities, two high school teachers, a school district administrator, and a statewide non-profit foundation director. The participants of the Academy included both rural teachers and students. Initially, funding was provided by the US Army exclusively. The initial funding was a modest amount and was awarded as a pilot study. The award was for one year at $25,000 and was later increased to $50,000 per year. However, when the Army funded ended after five years other program partners contributed to support the program for two reasons. The first reason is that the program expenses were not costly, and the second more compelling reason was that the program partners recognized the success of the program. Rural teachers and students completed research projects and successfully competed in STEM events against daunting odds including crippling snowstorms, massive hurricanes, and school relocation.

The program expenses initially covered educator stipends to encourage their participation, refreshments for students to meet on the weekend, and travel expenses for university and master teacher mentors. The other budgeted expense built into the program was for research materials and supplies. Program partners assumed that students would need funding to support their research ideas, especially if their research work was to be competitive in the statewide STEM competitions typically populated by students who have been mentored at university labs or advanced STEM schools. Project partners anticipated the cost of renting lab space, paying for use of expensive analytical equipment, chemicals, glassware, rare metals, etc. However, what we did not realize is the resourcefulness of the students and the fact that their ideas for research focused on meeting a local or community need that did not necessarily equate to a need to purchase expensive supplies and materials or rent or use expensive equipment. Even when we offered to purchase new supplies for projects students often refused and found items readily available from family or recycled materials rather than purchase new materials. For example, one student in the western North Carolina mountains wanted to research windcatchers as a way to provide air conditioning without increasing energy costs. He was interested in researching this passive cooling system because of the increasing number of days of higher temperature due to climate change. Currently most homes in western North Carolina do not have central air conditioning. Project partners offered to purchase new piping (duct work) for his experimental set up in an outbuilding on his property, but his father had found a home that had been remodeled, and the piping (duct work) was available for free reuse, so the student refused our offer. This is just one example of many of how our offers to purchase supplies were often turned away by students who found what they needed from their peers, family, and others in their rural communities. This is very much a benefit of rural life either in the mountains or on the coast of North Carolina.

Table 1. NC STEM Research Academy Schedule

Assignment	Assignment Description (Note: Students should have at least 12 weeks to do their projects)	Meetings
Teacher Training	Professional Development Training -Research Methodology and Working with Students	Overview In Person East and West Cohorts
Selection & Permission	AEOP Teachers Announce and Select Students for Program. Students must sign participation contract.	Completed at School
Topic Selection	Students need to select a topic area and propose a researchable question or engineering design project.	Project Partners meet virtually with Teachers prior to Student Meeting Virtual 9-Noon, Saturday
Research Plan	Mandatory for ALL Students.	Submitted to Project Partners
Research Paper & Poster Content	Meeting to discuss research paper format and content that can and should be used for Poster content. Review sample papers and posters from past STEM competition.	Project Partners meet virtually with Teachers afterschool. Student Meeting Virtual 9-Noon, Saturday
Experimental Design Materials & Procedures	An explanation of Variables, Independent, Dependent, Controls. A detailed list of the materials that will be used to conduct the experiment and must be submitted to project partners for purchase.	Project Partners meet virtually with Teachers afterschool. Student Meeting Virtual 9-Noon, Saturday
Data Overview	Students NEED to provide good data analysis for their projects. At a minimum mean, median, mode, and standard deviation need to be provided and discussed. Students should consider using inferential statistics to support their research questions.	Project Partners meet virtually with Teachers afterschool. Meet with Students In-Person East and West Cohorts.
Conducting the Experiment	There should be a minimum of two weeks to allow the students to do multiple runs of their experiments. Minimum Trials: 5 runs of experiment/trials. Engineering Design: List Test Parameters	Completed with Teacher Facilitation
Data Analysis & Graphs	The analysis of the experimental data. A summary of the findings of the experiment or testing engineering design.	Project Partners meet virtually with Teachers afterschool. Student Meeting Virtual 9-Noon, Saturday
Final Report/ Posters	A report that collects all the above written assignments with an explanation of results. Preparation of project abstract.	Completed with Teacher Facilitation

Display Board	Draft Project Board and Presentations	In-person Joint Meeting East and West Cohorts
STEM Competitions	Held Throughout Spring Academic Semester	

Project partners began with a two-day teacher training for teachers to explain the goals and learning objectives of the Academy, to demonstrate activities, and to share program materials for student participation. The Academy begins at the start of each academic year in late August or early September and students work through mid-February to be prepared to present in a statewide STEM competitions held throughout the Spring. Project partners mentor formally between eight to ten days during the Academy. Prior to Covid pandemic, mentoring was done onsite and in person but post-Covid, mentoring was primarily completed virtually. The format of the Academy sequentially follows the steps of scientific research or engineering design. Many teachers have stayed with the program for eight years and know what research activities the students need to complete in what progression to prepare them for the STEM research competitions. Table 1 provides the schedule of the NC STEM Academy Research tasks.

Why is the NC STEM Research Academy Successful?

The key to working with rural students is identifying and working with a teacher who will in turn support students. The essential first step to a successful STEM research program and the success of the NC STEM Academy is locating rural teachers who want to participate. The initial stipend of $800.00 helped entice teacher participation. Each teacher was expected to work with four to five students facilitating research work. Teachers were expected to attend all Academy virtual and in-person meetings during the academic year. What project partners know is that rural students prefer to work with people they know and do not prefer to work with strangers especially from outside their communities. Identifying a teacher research partner for students is critical. However, a strong teacher advocate who supports students is a universal benefit in high school regardless of geographic location. High school students, like all students, appreciate and benefit from strong, supportive teachers. Students perform better and are motivated to learn when positively encouraged and taught by a caring, supportive educator. Rural teachers know their students and families and are visible and well-known in their community. Typically, the rural school is one of the largest employers in the community and a teacher most likely knows the parents and has probably taught siblings of students. Knowing this, project partners sought out rural teachers interested in facilitating research projects for students in their content area, mainly in biology and environmental science.

The teachers would be provided with a small stipend and training and sustained with support by project partners. Because student STEM research is not a required in the NC course of study for either science or math, students would need to work on their research projects after school.

Therefore, participating teachers would have to understand that they would need to dedicate time after school to the NC STEM Academy. Project partners worked with school district personnel in the western and eastern NC areas to identify teachers who would be willing to participate.

According to The National Academies of Sciences, Engineering, and Medicine; Education, 2024*,* rural teachers tend to be less qualified in STEM because they are generally paid less, and locations are geographically less desirable. In addition, rural teachers who are willing to work with students conducting STEM research typically have little to no experience with research themselves. Project partners expected to identify teachers and knew that many would not stay with the program. In total, more than 25 teachers have participated in the Academy and today we have five teachers who have continued with the program since its inception. Of these five teachers, two worked outside the classroom prior to becoming teachers. One educator worked as a biomedical laboratory technician, and another worked as a water quality scientist with the U.S. Environmental Protection Agency. These STEM experiences enabled these educators to serve as role models to the other educators. They reinforce good research practice instruction with the teachers and help mentor all students during Academy meetings, in-person and virtual. Other teacher participants left the program due to family changes, school changes, and two teachers moved out of the state. The coastal area of North Carolina is home to military bases and so both teachers and students move in and out frequently due to reassignments.

The initial teacher training was held so project partners could overview the Academy goals and model the initial steps to conducting STEM research. It is essential to provide clear and concise goals for the educators. The NC STEM Academy initially met on Saturdays to model research instruction and activities for the teachers and students. The goal was to "train' the teacher and educate the students so that the teacher could then sustain the program year after year with minimal support from the project partners. Each Academy meeting was designed with the purpose of preparing a final research paper and poster for STEM competitions held throughout the spring in North Carolina. With this endpoint in mind, each Academy event included time spent with students and teacher participants reviewing, evaluating, and reporting on past competitive high school student posters. These artifacts included past high school student posters from various competitions from within the past three years that were national or state-winning posters and some that did not place. Academy participants met in groups to review the posters, and they used existing judging rubrics from the International Science and Engineering Fair (ISEF) or other competition rubrics to judge the posters. This process allowed them to learn the framework for and expectations of their research work for competitions. The students had an endpoint to work towards based on seeing finished research papers and posters prepared by other high school students. An example of an award winning poster is provided in Figure 1.

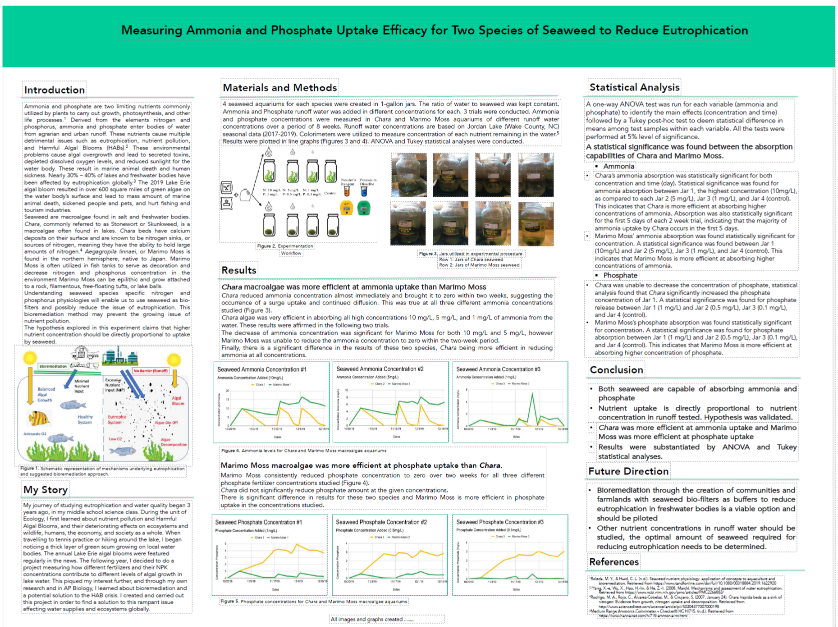

Figure 1. Sample High School Research Poster

One challenge of research for high school students is identifying a reasonable researchable question, hypothesis, or engineering problem statement. When surveyed at the end of each academic year, teacher participants listed that the most difficult challenge for them was facilitating students through their selection of a topic for research. Almost all rural students are new to research and have little to no experience with either the scientific method or engineering design process. One advantage for rural education is local rural or place-based knowledge of residents. Avery (2013) says that rural students who are engaged with their local environment and issues can make connections beyond their school environment directly impacting their community. The National Academies of Sciences, Engineering, and Medicine; Education (2024) suggests that STEM is inherent in rural communities, especially those tied to "agriculture, coastal communities, and remote communities that rely on a subsistence economy (p. 18)." The STEM Academy students from western and eastern NC did make connections to their communities based on their rural places and knowledge. Rural areas are a great place for learning science and engineering with access to natural areas, work in agribusiness such as farming or fishing. Many rural students learn to develop engineering and science skills in their daily lives to solve problems and fix equipment in their daily work activities. This type of experiential learning increases students' knowledge and ability to achieve in STEM course work and to take on a STEM research project. Below is a table of project titles from student research projects from western and eastern rural NC students. It is just a sample of projects students have undertaken but it is clear the students understand their community context and want to be helpful or solve a problem that is local.

Another source of knowledge for rural students is their families with their accumulated wisdom, hands-on knowledge of jobs and careers, where they have lived, the history of a region, people, traditions, and cultural practices. The concept of "funds of knowledge" by Luis Moll (2005) is that people have knowledge learned from their life experiences. The most direct way of accessing students' funds of knowledge is to get to know as much as possible about the student. A good start is to find out what the student might be interested in researching in the context of their family and community. See Figure 2.

Table 2. List of Student Research Projects

Name	Research Project Title	School
Student A	Impacts on Local Air Quality from Personal Burn Barrells	Onslow Early College High School
Student B	Developing a Biodegradable Water Bubble Solution to Reduce Plastic Water Bottle Waste	Onslow Early College High School
Student C	*The Effects of Various Plants on Fertilizer Runoff*	Onslow Early College High School
Student D	ENO River Quality	Onslow Early College High School
Student E	The Cost Efficiency of Store Bought versus Home-Made Compost for Plant Growth	Northside High School
Student F	Cost Efficiency of Vertical Solar Panels	Onslow Early College High School
Student G	How Does Renaming a Military Base Affect Local Communities	Northside High School
Student H	The Impacts of Microplastics on Plant Growth and Soil Health	Onslow Early College High School
Student I	*Quantitative Analysis of the Effects of Agricultural Absorption Rates on Greenhouse Gas Pollutant*	Avery High School
Student J	Using Coding and Condensed Microphones to Determine the Location of a School Shooter	Avery High School
Student K	Mycofiltration Within Bacterially Polluted Waters	Avery High School
Student L	Revolutionizing Kudzu into a Sustainable Bioplastic	Watagua High School
Student M	Utilizing Lagenidium giganteum to Eradicate Mosquito Larvae	Watagua High School

STEM Research Project Brainstorming Worksheet Name:

I. Brainstorming List (Places, Natural Areas, People, Events) Who do you know? What do they do? How can they help? What tools or things do they have they can share with you?

II. Two general areas of STEM interest:

1.	2.

Two specific problems for each area of interest:

1A	2A
1B	2B

III. Brainstorming Questions Now choose one problem from above. Answer the questions below only for the problem of greatest interest from above.

1. **What materials are readily available to me for conducting experiments or designing a model or prototype on this topic?**
2. **How does the topic act or respond? OR what type(s) of behavior or performance will it exhibit?**
3. **What types of materials could be used to cause this topic to react or show change?**
4. **How can you measure a response or change?**

Figure 2. STEM Research Project Brainstorming

We learned a great deal about the participating students when they completed the STEM brainstorming worksheet (Figure 2). We know these students have strong, extended families in the area and that they rely on their family members, community contacts, and friends for information and resources rather than relying on outside assistance. We were able to identify STEM resources and STEM expertise that other students' family members willingly offered to provide other students. Academy members, both project partners and teachers, realized that we would not have many of the research projects from high-achieving students we typically see from mentored research labs, but we would have good, strong well conducted science and engineering projects from students who cared about and are connected to their work. The measure of success was not winning the STEM competitions but rather knowing students understood and appreciated what they gained from the research process. Most Academy students participated throughout high school until graduation and so many of the alumni have gone on to continue STEM research in their undergraduate studies. They have gone on to attend Columbia University, University of South Carolina, North Carolina State University, University of North Carolina, and more. These students have told us that their experience in the NC STEM Academy gave them the confidence to pursue STEM coursework in engineering, bioengineering, medicine, at the undergraduate level.

There were a few students that were unable to participate not because of interest but because of life circumstances. One student did not have the time or means to attend the after-school sessions because they needed to stay at home to care for their younger siblings. Both their parents work as migrant farm workers, and one parent had recently had a bad accident using farm machinery and could not work nor care for the younger siblings. Another student was unable to participate because the parents who did not speak English as a first language were anxious about traveling to participate in events outside of their community.

Mentoring Rural Students

Mentoring rural students in science research requires both creativity and flexibility. By leveraging local expertise, identifying less traditional mentors, and creating opportunities for students to refine their protocols and present their work publicly, educators can make authentic science accessible outside of large urban centers. Approaches such as pairing students with local scientists, connecting them to near peers, and offering structured feedback through showcases empower rural youth to see themselves as capable contributors to scientific inquiry.

Equally important are new approaches that use technology to bridge geographic isolation. Virtual mentoring, remote lab access, and digital collaboration platforms allow students to interact with experts, refine their projects, and receive ongoing guidance. These strategies broaden access to mentorship networks and ensure that rural students are not left behind in developing 21st-century scientific skills. Ultimately, building sustainable mentoring systems requires partnerships among schools, universities, local communities, and professional organizations. By widening the definition of who can serve as a mentor, whether a teacher, scientist, college student, or industry professional, rural students can access multiple pathways to experience authentic research collaboration. These connections foster not only scientific understanding but also confidence, resilience, and a sense of belonging in a STEM community.

Project partners initially drove to western and eastern NC, each trip several hours to meet with teachers and students. These Academy meetings took place on Saturdays and were packed with activities, discussions, and group work. The effort required time and expense for the four to five project partners, travel expenses, Academy expenses, snacks and lunch for the students in addition to the pre-planning for each meeting. When the Covid pandemic hit, partners had to pivot quickly to an online platform to complete the year. It quickly became apparent that the teachers were more than capable of sustaining the program onsite while project partners could join virtually to provide group activities, discussion, and mentoring. Students meet with partners virtually at assigned times who give them feedback at all stages of their research journey.

Community Resources for Rural Students

Community-based programs can draw on local expertise and environmental features, such as farms, forests, rivers, beaches, and mountains to create meaningful learning experiences (Avery, 2013). This local context helps students see the relevance of science and engineering to their own lives builds connections to place and a sense of belonging to community. Because of the nature of STEM learning in rural areas, STEM education can occur in a variety of environments, from classrooms to museums, zoos, online, the home, parks, gardens, and other natural areas. In eastern North Carolina, a main resource for students is the local military base. Not only are there STEM personnel, engineers, information technology, etc. but there are plenty of service industries off-base that students can connect with for information and assistance. The eastern NC student cohort also has access to coastal water research laboratories. These governmental and non-profit organizations study marine animals and water quality. In the western NC region of the state an important industry is ecotourism. Keeping water quality pristine, commercial land development is limited, and biodiversity is encouraged. This focus and the organizations, Soil and Water Conservation, Park and Recreation Department, etc. are all useful community organizations students can work with to collect data, review methodology, results and to share their findings and results.

Conclusion: Program Success & Implications

The NC STEM Academy demonstrates that rural students can engage in authentic research experiences when supported by dedicated teachers, mentors, and community partners. Program success rests on three central practices: (1) selecting partners who are committed to increasing rural student participation in STEM research and engineering design projects, (2) engaging rural students, teachers, school administration who will actively participate in STEM research opportunities, and (3) cultivating relationships with universities, businesses, and community groups to expand access to STEM mentoring, resources, internships, and funding partnerships. This work affirms Boyer's (2006) insight that effective rural education "offers a deep respect for rural life and honors the determination of residents to sustain rural communities. It's inherently interdisciplinary, project-based, and it builds on local resources and expertise" (p. 115).

The implications are clear: research-based, project-driven mentoring in rural areas is not only feasible but transferable. As Rural Education at a Glance (USDA Economic Research Service) shows, higher levels of educational attainment directly support stronger economic outcomes in rural areas. When rural schools invest in research they contribute to long-term community sustainability by preparing students for both higher education and the modern workforce.

- Sustaining and scaling this model requires intentional collaboration. Our model follows closely the criteria for educating a rural workforce suggested by the U.S. Department of Agriculture's Economic Research Service Rural schools (2017) and includes:
- **Using place-based education:** This connects research work with local resources, history, and the environment to explore real-world learning opportunities.
- **Establishing strong partnership between teacher and student researchers:** This promotes consolidation of resources, knowledge, and expertise.
- **Creating professional networks:** Partnerships among community business, industry and education allow rural teachers and students to develop mutually beneficial relationships.
- **Engage universities in "grow-your-own" initiatives**: This will strengthen the pipeline of rural educators and encourage students to pursue STEM careers
- **Partner with businesses and higher education institutions:** This provides an excellent directory for research mentoring and assistance.

By leveraging these strategies and resources, the NC STEM Academy model shows how rural schools can create sustainable pathways to STEM success. The result is not only stronger individual outcomes for students but also the revitalization of rural communities through education, workforce readiness, and innovation.

Program Success and Implications

The NC STEM Academy successfully engaged high school teachers and students in STEM research by 1) Choosing individuals from local schools and the community strongly committed engaging in research and engineering design projects; 2) Working with rural students, teachers, families, community members, and organizations so pipelines to STEM higher education and career pathways remain open to rural students; and 3) Pursuing and cultivating relations with various organizations to provide rural students with formal experiences in STEM through shared resources, mentoring, and internship

Resources*:* Implementation Guide: Starting a Rural STEM Research Program

For educators and communities interested in replicating the NC STEM Academy model, the following steps provide a practical roadmap.

- Needs Assessment: What are the local strengths, what gaps exist (e.g. lab equipment, mentor access, teacher training), what are anticipated costs?
- Stakeholder Engagement: Involve students, teachers, families, local scientists/industry from the beginning.
- Pilot Project: Start with a small research project (e.g. local environmental science, agricultural research, citizen science) to pilot program activities, mentor connections, student interest.
- Resource Mapping: What community colleges, business, industry, governmental organizations are within reach? Are there online platforms, virtual labs if physical labs are too far or expensive?
- Evaluation and Feedback: Build in ways to assess what works, collect feedback, refine protocols.
- Scaling & Funding Strategy: Once pilot is successful, seek funding, formalize partnerships, maybe build a pipeline (e.g. mentorship → summer research → showcase → further opportunities).

Best Practices for Program Success in Rural Communities

- Project-based, place-based learning: Anchoring research projects in the local environment (ecology, agriculture, local issues) helps engage students and draw on local expertise.
- Virtual mentorship / collaboration: Use of remote scientists, online lab simulations, virtual research tools so that rural students aren't limited by lack of local resources.
- Partnerships: With universities, industry, extension services, museums, community organizations. These can provide mentor help, provide equipment and sites for fieldwork.
- Teacher professional development: Model research process for teachers using inquiry-based methods, scientific research skills,

project management, data analysis etc.

- Local capacity building: Building from local knowledge (community practices), leveraging what is available (land, community, existing facilities).
- Sustainability planning: Securing multi-year funding, integrating with school district priorities, involving families and community, embedding programs so they survive beyond individual champions.

By following these steps, rural schools can adapt the NC STEM Academy framework to their own contexts, creating sustainable pathways to STEM success and ensuring that students are prepared for both higher education and the modern workforce.

References

Avery, L. M. (2013). Rural science education: Valuing local knowledge. *Theory Into Practice,* 52(1), 28–35. https://doi.org/10.1080/07351690.2013.743769

Boyer, P. (2006). Building community: Reforming math and science education in rural schools. *Fairbanks, AK: Alaska Native Knowledge Network.* Downloadable at http://www. ankn. uaf. edu/Publications/building_community. pdf

Brown, K., Heise, N., Nelson, J., Hall, H., Ivie, K., Meyer, C., Eitel, C., Walrond, J., & Clapp, T. (2021). Engaging rural high school students in STEM utilizing graduate mentors, virtual reality, and case-based learning. *The FASEB Journal, 35*(S1), Article fasebj.2021.35.S1.03790. https://doi.org/10.1096/fasebj.2021.35.S1.03790

De Mars, A., Taken Alive, J., Burns Ortiz, M., Ma, Z., & Wang, M. (2022). Educators' perspectives on factors impacting STEM achievement in rural Indigenous student-serving schools. *The Rural Educator, 43*(1), 24–36. https://doi.org/10.35608/ruraled.v43i1.1207

González, N., Moll, L. C., & Amanti, C. (Eds.). (2005). *Funds of knowledge: Theorizing practice in households, communities, and classrooms*. Lawrence Erlbaum Associates.

Grimes, L. E., Arrastía-Chisholm, M. A., & Bright, S. B. (2019). How can they know what they don't know? The beliefs and experiences of rural school counselors about STEM career advising. *Theory and Practice in Rural Education,* 9(1), 74–90. https://doi.org/10.3776/tpre.2019.v9n1p74-90

Marksbury, N. (2017). Monitoring the pipeline: STEM education in rural U.S. *Forum on Public Policy, 2017*(2). https://forumonpublicpolicy.com/vol2017.no2/marksbury.pdf

Morris, J., Slater, E., Fitzgerald, M. T., Lummis, G. W., & van Etten, E. (2021). Using local rural knowledge to enhance STEM learning for gifted and talented students in Australia. *Research in Science Education,* 51(Suppl 1), 61–79. https://doi.org/10.1007/s11165-019-9823-2

National Academies of Sciences, Engineering, and Medicine. (2024). *K–12 STEM education and workforce development in rural areas* (E. T. Cady, K. Frase, & T. Neill, Eds.). National Academies Press. https://doi.org/10.17226/28269

National Center for Education Statistics. (2023). Rural students' access to the internet. *Condition of Education*. U.S. Department of Education, Institute of Education Sciences. https://nces.ed.gov/programs/coe/indicator/lfc.

Public Schools First NC. (2025, February 1). *The facts on rural schools – public schools first NC*. The Facts on Rural Schools. https://publicschoolsfirstnc.org/resources/fact-sheets/the-facts-on-rural-schools/

Rivera, S., Kiiza, I., Kavanagh, K., DeWaters, J., Galluzzo, B., & Ramsdell, M. (2023). Challenges and opportunities for STEM teachers in rural schools: A case study. *Thresholds in Education,* 46(3), 420–439.

Showalter, D., Hartman, S. L., Eppley, K., Johnson, J., & Klein, R. (2023). *Why rural matters 2023: Centering equity and opportunity*. National Rural Education Association. https://www.nrea.net/why-rural-matters

Tran, H., Hardie, S., Gause, S., Moyi, P., & Ylimaki, R. (2020). Leveraging the perspectives of rural educators to develop realistic job previews for rural teacher recruitment and retention. *The Rural Educator, 41*(2), 31–46. https://doi.org/10.35608/ruraled.v41i2.866

United States Department of Agriculture, Economic Research Service. (2017). *Rural education at a glance, 2017 edition* (Economic Information Bulletin No. 171). https://www.ers.usda.gov/webdocs/publications/83078/eib-171.pdf

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INNOVATIVE PRACTICES IN STEM EDUCATION

Emerging Technologies, Pedagogies and Learning Models

Innovative Practices in STEM Education: Emerging Technologies, Pedagogies and Learning Models examines how contemporary pedagogical approaches and emerging technologies can be effectively integrated to design meaningful, equitable, and sustainable STEM learning environments. This edited volume moves beyond technology-driven innovation by emphasizing the critical role of theory-informed pedagogy, curriculum design, and assessment in advancing STEM education. Drawing on diverse frameworks such as inquiry- and problem-based learning, computational thinking, gamification, variation theory, integrative STEM, and TPACK, the book illustrates how innovative practices support deep conceptual understanding, creativity, and collaboration across STEM disciplines. Mathematics is positioned as a unifying discipline that connects science, technology, and engineering through modelling and problem solving. With a strong focus on implementation and equity, the volume presents international case studies and research-based examples from face-to-face, hybrid, and virtual contexts, including rural and underserved settings. By critically examining emerging technologies—such as augmented reality, metaverse environments, open-source platforms, and game-based learning—alongside STEAM, entrepreneurship, and community-based initiatives, the book offers a comprehensive and practice-oriented perspective. Intended for researchers, educators, and policymakers, this volume provides an evidence-informed roadmap for developing coherent, inclusive, and future-ready STEM education practices.

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