

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, Velychko et 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.

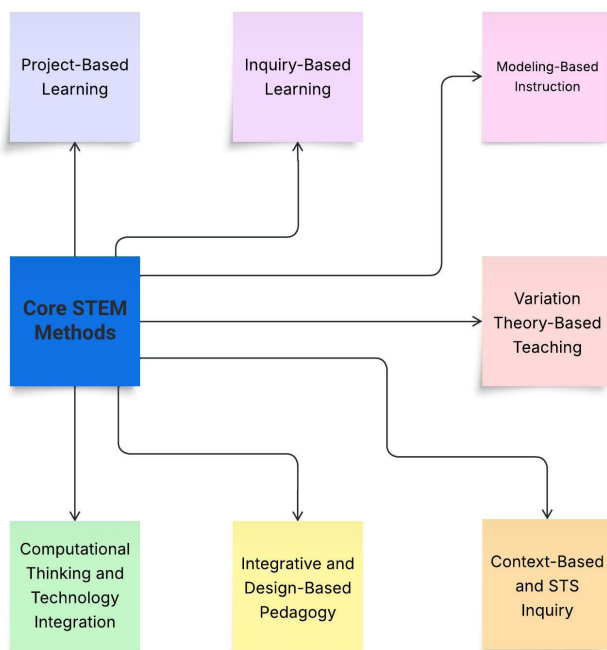


Figure 1. Core STEM Teaching Methods Examined in This Chapter

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.

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