Eurasian Journal of Science and Environmental Education
2025, 5(1), 11-17
ISSN 2672-863X (Online)
https://www.ejsee.com/
Review Article
OPEN ACCESS

Integrating learning theories and innovative pedagogies in STEM education: A comprehensive review

Leonidas Gavrilas [1]*, Konstantinos T. Kotsis [1]

[1] Department of Primary Education, University of Ioannina, Ioannina, GREECE
***Corresponding Author:** l.gavrilas@uoi.gr

Citation: Gavrilas, L., & Kotsis, K. T. (2025). Integrating learning theories and innovative pedagogies in STEM education: A comprehensive review. *Eurasian Journal of Science and Environmental Education*, 5(1), 11-17. https://doi.org/10.30935/ejsee/16538

ABSTRACT

STEM education integrates science, technology, engineering, and mathematics to tackle complex real-world challenges. This paper examines five key learning theories—constructivism, social constructivism, experiential learning, cognitive load theory, and situated learning—and assesses their roles in improving STEM pedagogy. It reviews the impact of each theory on curriculum design, classroom engagement, and higher-order thinking. A special emphasis is placed on inquiry-based, problem-based, and collaborative learning, as well as flipped classrooms, highlighting how these methods implement theoretical principles through learner-centered, hands-on activities. Significant challenges include professional development, effective scaffolding, authentic assessment, and opportunities to foster 21st-century skills. By combining theoretical and practical perspectives, this paper emphasizes the significance of a theory-informed approach that promotes critical thinking, creativity, and collaboration, ultimately equipping students for an increasingly complex global landscape.

Keywords: STEM education, learning theories, inquiry-based learning, problem-based learning, 21st-century skills

Received: 10 Feb. 2025 ◆ Accepted: 06 Jun. 2025

INTRODUCTION

Over the last few decades, science education has undergone a fundamental shift, moving away from traditional teacher-centered paradigms toward more holistic, integrated, and learner-centered approaches. One of the most prominent examples of this transition is STEM education, which merges four distinct but interconnected fields—Science, Technology, Engineering, and Mathematics—into a cohesive framework designed to prepare students for the complexities of the 21st century (Penprase, 2020; Tytler, 2020). Although the term "STEM" was officially adopted around the turn of the millennium, its conceptual roots reach back to reform initiatives that emerged in the late 20th century, intended to boost scientific literacy, technological fluency, and economic competitiveness (Holmlund et al., 2018; Kotsis & Gavrilas, 2025; Li et al., 2020).

STEM education is an acronym that groups four subjects and is an integrated paradigm where students learn to solve real-world problems by applying interdisciplinary knowledge. This integrated model inherently relies on theories of learning that shift the emphasis from the passive reception of information to an active, reflective, and socially mediated construction of knowledge. Traditional education often compartmentalized science or mathematics, reducing them to the rote memorization of content. In contrast, STEM education aims to interweave scientific inquiry, design thinking, and mathematical rigor in a way that fosters critical thinking, creativity, teamwork, and scientific literacy (McComas, 2014; Mohd Najib et al., 2020).

Central to this shift are various theories of learning—constructivism, social constructivism, experiential learning, cognitive load theory, and situated learning—that all share a common feature: the learner is seen as an active participant. Rather than framing learning as the passive reception of information, these theories contend that knowledge is constructed, negotiated, applied, and internalized through authentic engagement with the environment, the community, and one is prior experiences (Kolb, 1984; Sweller et al., 2011; Vygotsky & Cole, 1981).

Simultaneously, multiple teaching methods have emerged or gained renewed emphasis in STEM contexts, drawing heavily on the aforementioned theoretical frameworks. The principal examples are inquiry-based learning, problem-based learning (PBL), collaborative learning, and the flipped classroom model. By exploring these methods in conjunction with core learning theories, educators gain potent tools to create meaningful, learner-centered environments where students not only absorb scientific facts but also develop the capacity to innovate and adapt in a rapidly evolving world (Kelley & Knowles, 2016; Stehle & Peters-Burton, 2019).

This paper comprehensively examines the major learning theories and teaching methods in STEM education, centering on five influential theoretical perspectives—constructivism, social constructivism, experiential learning, cognitive load theory, and situated learning. It explores how these perspectives align with STEM education's core principles, emphasizing their shared foundations and unique contributions. The discussion then turns to four prevalent teaching approaches—inquiry-based learning, problem-based learning, collaborative learning, and the flipped classroom—and critically investigates how each applies specific learning theories to foster students' STEM competencies.

THEORETICAL FOUNDATIONS: KEY LEARNING THEORIES

Constructivism

Constructivism is founded on the premise that learners actively construct their understanding of the world through experience and reflection (Piaget, 1964). Jean Piaget's pioneering work viewed cognitive development as a process of successive restructuring of mental schemas, which results from the learner's constant interaction with the environment. In a Piagetian sense, individuals assimilate new information into existing schemas and accommodate their schemas when new experiences do not fit.

Within STEM education, this theoretical stance has profound implications for classroom practice. In a constructivist classroom, the role of the teacher shifts from a transmitter of knowledge to a facilitator who creates experiences and poses challenges that invite students to actively engage with scientific and mathematical ideas (Patel, 2019). Rather than having students memorize formulas in isolation, constructivist STEM classrooms feature tasks that allow learners to explore, experiment, and refine hypotheses.

The active nature of constructivist learning aligns particularly well with the problem-solving ethos of STEM. In a science laboratory, for instance, students might be asked to design an experiment on friction by formulating hypotheses and analyzing their data. Instead of viewing friction as a static concept, students are encouraged to discover the underlying principles, comparing predicted outcomes with actual results. This fosters more profound conceptual change as the new knowledge is integrated into existing cognitive frameworks.

Furthermore, constructivism highlights the need to link new content to learners' existing knowledge. If a group of learners explores geometric concepts, a constructivist approach would suggest beginning with intuitive shapes or real-life applications (like measuring the classroom area) before progressing to abstract formulae. By making students aware that they are bringing prior ideas to new learning tasks, educators can help them reorganize and refine their conceptual schemas (Koç Akran & Aşiroğlu, 2018; Kotsis, 2025).

Social Constructivism

Social constructivism extends the principles of constructivism into the social realm, suggesting that knowledge construction is not solely an individual pursuit but occurs in collaboration with others (Vygotsky & Cole, 1981). Lev Vygotsky underscored the influence of cultural and social contexts on cognitive development, introducing the concept of the "Zone of Proximal Development" (ZPD). The ZPD represents the gap between tasks learners can accomplish independently and those they can accomplish with teacher guidance or more knowledgeable peers.

In STEM education, social constructivism manifests in collaborative projects and peer-to-peer interaction, enabling students to co-construct knowledge, refine it through debate, and internalize deeper conceptual meanings (Shabani, 2016). For example, a group of students working on a robotics project might face technical challenges extending beyond any student's immediate capabilities. Students engage in reciprocal learning by working collectively, sharing insights, and offering mutual support. The teacher's role involves scaffolding: providing initial hints or resources, then gradually withdrawing assistance as students gain competence.

This social dimension is particularly crucial to STEM fields, which often require interdisciplinary collaboration in real-world situations. Scientists, engineers, and technologists frequently work in teams to address complex problems, and the school environment should mirror such collaborative processes. By organizing small-group discussions and interactive workshops, teachers allow learners to articulate their thoughts, confront misconceptions, and develop refined solutions through group discourse (Saleem et al., 2021).

Experiential Learning

Experiential learning theory, most notably articulated by David Kolb (1984), holds that knowledge creation is a cyclical process involving concrete experience, reflective observation, abstract conceptualization, and active experimentation. Learners continuously move through these stages to refine their understanding. Suppose a student encounters a new phenomenon in physics, such as projectile motion; an initial hands-on experience with launching small projectiles can generate raw observations. The learner then reflects on these observations, forming theoretical constructs about gravity and velocity, and subsequently tests those ideas in new situations.

The significance of experiential learning for STEM lies in its emphasis on "learning by doing." STEM inherently deals with phenomena that can often be observed, tested, and manipulated in practical settings—through lab experiments, engineering projects, and field excursions (Remington et al., 2023). Students do not merely read about a concept; they test it in tangible contexts. This kind of active engagement has increased motivation as learners see the relevance of scientific principles in real-world contexts, ranging from environmental issues to technological design (Gontas et al., 2021; Papanikolaou et al., 2021).

Moreover, experiential learning supports the development of metacognitive skills. Students are encouraged to reflect on the process, identifying what worked, what did not, and why. For example, a student building a simple electrical circuit may discover that an incorrect connection leads to a short circuit. Through experience and reflection, students develop technical competence and the habit of iterative thinking, which is essential in many STEM professions (Gavrilas et al., 2025; Lestari, 2021).

Cognitive Load Theory

John Sweller's cognitive load theory focuses on how cognitive resources are allocated and how instruction can be designed to optimize the use of a learner's working memory (Sweller et al., 2011). STEM disciplines often feature intricate equations, multi-step problem-solving processes, and abstract concepts that can overload working memory if not structured carefully.

Cognitive load is often divided into intrinsic load (complexity inherent in the content), extraneous load (caused by poor instructional design), and germane load (mental effort that contributes to schema construction). For example, the intrinsic load might be high in a mathematics lesson on integrals because of the conceptual complexity. However, extraneous load can be minimized by providing clear diagrams and a step-by-step approach rather than dense text with no scaffolding (Paas et al., 2016).

In STEM education, teachers who adopt strategies to reduce extraneous load—such as using well-labeled diagrams, chunking instructional content, or employing guided practice—free up cognitive capacity for meaningful learning. This approach aligns with the overarching emphasis on deeper conceptual understanding because students can focus less on superficial cognitive tasks (decoding poorly structured instructions) and more on analyzing, synthesizing, and applying STEM knowledge.

Situated Learning

Situated learning theory, advanced by Jean Lave and Etienne Wenger (1991), posits that learning is most effective when embedded in the cultural, social, and physical contexts in which it will be used. Instead of viewing knowledge as a set of abstract concepts that can be transmitted in isolation, situated learning sees knowledge as a product of authentic participation in a community of practice.

In STEM classrooms, situated learning might be operationalized by partnerships with local industries, service-learning projects, or cross-disciplinary activities that mirror professional engineering or research processes (Aguilera et al., 2024). Students who collaborate with a local company to design an energy-efficient device for actual community use gain a sense of authenticity. They see how theoretical mathematics, scientific principles, and engineering design converge in practical problem-solving.

This authenticity cultivates motivation and helps students internalize knowledge as they witness its direct utility. They also become socialized in STEM fields, adopting relevant discourse, norms of inquiry, and collaborative habits. This approach aligns seamlessly with STEM's collaborative and application-oriented nature, as it fosters the accumulation of facts and the development of professional dispositions and identities (Pfeiffer & Bradbury, 2023).

THEORIES IN THE CONTEXT OF STEM EDUCATION

The learning theories discussed are complementary rather than mutually exclusive, and their integration enriches STEM education in multiple ways. Constructivism and social constructivism underscore that learners actively build knowledge through meaningful engagements and social interactions, a perspective particularly relevant in STEM, where problem-based learning thrives on group dialogue and critical thinking. Experiential learning resonates with the practical orientation of scientific inquiry, technological design, and engineering challenges, reinforcing the principle that knowledge must be applied to be internalized. Cognitive load theory underscores the importance of strategic instructional design—an especially pertinent point given many STEM topics' abstract, multi-layered nature. Situated learning emphasizes context, authenticity, and community, adding a "real-world" dimension to STEM tasks.

Each theoretical lens contributes to how educators conceptualize classroom activities, structure content, and evaluate student outcomes. Where constructivism and social constructivism place the learner's active role and social milieu at the forefront, cognitive load theory and experiential learning focus on optimizing mental effort and hands-on practice. Situated learning integrates these approaches into authentic settings, reminding teachers that the deeper purpose of STEM is to enable students to operate effectively in accurate or realistic contexts.

STEM education is consistently described as interdisciplinary, context-driven, and future-oriented. The shift toward integrated STEM amplifies the necessity to design activities where mathematics supports engineering projects, science underpins technology solutions, and technology becomes a vehicle for modeling scientific phenomena (Gonzalez & Kuenzi, 2012). Learning theories provide the rationale for choosing and blending various instructional approaches to help students conceptualize the unity of these domains. This alignment is critical, considering that STEM programs often aim to cultivate innovators and critical thinkers who will address global challenges ranging from climate change to healthcare (Fung et al., 2022; Zhang et al., 2024).

Moreover, the demands of 21st-century skills—problem-solving, collaboration, creativity, and digital literacy—speak to the synergy among these theories (Chen et al., 2023; Gavrilas & Kotsis, 2024, 2025a). Constructivist and experiential perspectives reinforce creativity and problem-solving. Social constructivism naturally leads to collaborative learning experiences. Cognitive load theory ensures that instructional methods are not overwhelming, preventing disorientation. Situated learning cements these skills by situating them in meaningful and authentic projects. Indeed, research has shown that the best STEM outcomes emerge when theoretical constructs guide the design of learning environments that are hands-on, collaborative, cognitively accessible, and contextually meaningful (Tenney et al., 2023).

TEACHING METHODS IN STEM: LINKING THEORY TO PRACTICE

Contemporary STEM education highlights a broad spectrum of teaching methods. Each method, in its way, draws on and operationalizes elements from the major learning theories. Although the methods are conceptually distinct, they are frequently combined in practice to enrich learner experiences. This section discusses inquiry-based learning, problem-based learning, collaborative learning, and the flipped classroom. It highlights the theoretical underpinnings for each approach and examines how they foster higher-order thinking, motivation, and practical competence.

Inquiry-Based Learning

Inquiry-based learning places curiosity, questioning, and investigative processes at the core of instruction. Teachers act as facilitators, guiding learners as they formulate research questions, collect and analyze data, and draw reasoned conclusions. This approach embodies the essence of constructivism, as it nurtures active, exploratory behavior and resonates with the social constructivist idea of learning through peer interactions (Abdurrahman et al., 2019; Presnillo & Aliazas, 2024).

Inquiry-based STEM activities often involve science experiments, data-driven technology projects, or mini-engineering design tasks. The cognitive load theory is also relevant here since educators must structure inquiry activities to be scaffolded in ways that reduce extraneous load. For instance, a teacher might provide a guiding worksheet for data collection, thus enabling students to concentrate on formulating hypotheses and analyzing results rather than struggling with organizational details. Experiential learning is activated because learners "experience" phenomena directly and cycle through reflection, conceptualization, and active re-experimentation.

In a broader sense, inquiry-based instruction cultivates a mindset of scientific thinking. Students learn to see problems as open-ended, formulate testable hypotheses, and respect evidence-based reasoning. The teacher's role moves from delivering facts to coaching and prompting deeper questioning. As a result, inquiry-based learning can significantly improve students' capacity to investigate unknowns, which remains crucial whether they continue in STEM careers or not (Bybee, 2010).

Problem-Based Learning

Problem-based learning (PBL) involves students tackling actual or simulated real-life problems that do not have straightforward solutions (Hmelo-Silver, 2004; Hung, 2009). The method often begins with presenting a complex scenario—such as designing an environmentally friendly water filtration system—and invites learners to identify and research relevant scientific and mathematical concepts, apply technological tools, and propose engineering solutions.

Although PBL is conceptually close to inquiry-based learning, it diverges somewhat in its overt emphasis on real-world complexity and interdisciplinary collaboration. By design, PBL tasks are typically more open-ended, requiring input from multiple domains of STEM to devise feasible answers. From the perspective of social constructivism, PBL is ideal for encouraging group exploration, peer instruction, and negotiation of ideas. Cognitive load theory also factors into PBL design, as teachers need to break down overarching tasks into sub-problems or phases to ensure that novice learners do not become overwhelmed by the scope of the problem.

PBL's alignment with experiential learning is evident. Learners "learn by doing" and reflect on the processes that guide them toward (or away from) particular solutions. In this reflection, they refine their problem-solving approaches, conceptual understanding, and collaborative strategies. Situated learning comes into play if the problem replicates authentic conditions, such as a local environmental issue (Papanikolaou et al., 2023). PBL fosters a sense of relevance and urgency in these cases, making students more likely to internalize and retain new knowledge (LaForce et al., 2017; Rizki & Suprapto, 2024).

Collaborative Learning

Collaborative learning, while broad in definition, generally involves small groups of students working toward a shared academic objective. Unlike instructor-driven lectures, collaborative tasks rely on peer interactions as the principal driver of knowledge construction (Jeong et al., 2019; Meador et al., 2024). In a STEM context, this can manifest in group design challenges, co-creation of digital products, data analysis teams, or combined peer-teaching activities.

Social constructivism is the most explicit theoretical grounding for collaborative learning, as it suggests that cognitive development is enhanced by social discourse and collective problem-solving (Vygotsky & Cole, 1981). Nevertheless, collaborative settings can also incorporate elements of constructivism (as individuals refine their understanding within a group), experiential learning (groups engage in hands-on activities), and cognitive load theory (group members share the cognitive burden).

Furthermore, collaborative learning fosters essential 21st-century skills. Students hone communication, conflict resolution, leadership, and teamwork. STEM professionals often operate in multidisciplinary teams, rendering collaborative learning a microcosm of professional practice. In well-designed tasks, the teacher ensures that each member has a specific role—data analyst, hardware specialist, or documentation lead—thereby encouraging each learner to contribute specialized input while remaining part of a collective solution.

Flipped Classroom

The flipped classroom approach inverts the traditional instructional sequence by requiring students to engage with new content—often through video lectures, reading materials, or simulations—outside class time. Classroom sessions are then devoted to interactive discussions, collaborative problem-solving, or laboratory-based explorations (Cho et al., 2024; Gong et al., 2024).

This model has garnered substantial interest in STEM, given that class periods become opportunities for students to test, analyze, and expand upon prior learning through immediate feedback from teachers and peers. Regarding learning theory, the flipped model aligns with constructivist ideas by emphasizing active classroom engagement rather than passive lecture attendance. Social constructivism appears through in-class group tasks in which students clarify pre-studied material, question each other, and resolve misunderstandings. Cognitive load considerations are also relevant: Students can watch videos or review content at their own pace, pausing and rewatching material to manage their intrinsic load. Class time can then be dedicated to deeper tasks that require teacher guidance and peer collaboration.

The flipped classroom can integrate experiential learning if the in-class portion includes hands-on experiments or group-based project work, allowing students to transform theoretical content into real-life applications. Moreover, a STEM teacher might cultivate a situated learning component by connecting the day's application or project to authentic professional scenarios, such as analyzing big data sets from accurate scientific databases or simulating engineering prototypes.

CONCLUSION

STEM education seeks to convey disciplinary knowledge in Science, Technology, Engineering, and Mathematics and integrate these domains into a coherent learning experience that nurtures critical thinking, creativity, problem-solving, and collaborative skills. Learning theories such as constructivism, social constructivism, experiential learning, cognitive load theory, and situated learning form the theoretical backbone of this integrated approach. They underscore that knowledge emerges most robustly when learners can explore phenomena, reconcile new information with prior understanding, engage in dialogue and collaboration, participate in authentic and context-rich tasks, and do so in an environment where the cognitive demands are carefully regulated through effective instructional design.

Constructivism teaches us that students should not be mere data recipients; they need the autonomy to shape and reshape their conceptual frameworks. Social constructivism pushes us to design learning spaces that harness the power of peer interaction and shared meaning-making. Experiential learning insists on the primacy of direct involvement, reflection, and iterative experimentation, which dovetails perfectly with the hands-on dimension of STEM. Cognitive load theory serves as a cautionary guide, ensuring that complex tasks are scaffolded to facilitate learning rather than overwhelm it. Situated learning reminds educators and policymakers of the essential authenticity of knowledge, urging them to anchor STEM activities in inaccurate or realistic contexts where learners can discover the social and practical significance of science, technology, engineering, and mathematics.

The teaching methods highlighted in this paper—inquiry-based learning, problem-based learning, collaborative learning, and the flipped classroom—demonstrate how these theories become operational in real classroom settings. Inquiry-based and problem-based learning push learners toward open-ended investigation, ensuring they act as young scientists or engineers grappling with uncertainties and constructing knowledge through observation, experimentation, and peer discussion. Collaborative learning leverages social constructivist tenets by placing group interactions at the forefront of the educational process, thereby simulating the real-world teamwork that characterizes contemporary STEM fields. The flipped classroom reimagines time allocation in ways that maximize active, participatory learning in class while also affording students control over their pace of content acquisition.

Despite these methods' proven potential, challenges persist. STEM curricula often contend with limited resources, insufficient teacher professional development, and traditional assessment frameworks that fail to measure higher-order thinking skills or the capacity to apply concepts in novel contexts (Ejiwale, 2013; Gavrilas et al., 2024; Nadelson et al., 2013). Addressing these barriers requires systemic interventions, including investment in professional learning communities for teachers, aligning policies and curriculum standards with integrated STEM goals, and developing more valid and authentic assessment tools (Gavrilas & Kotsis, 2025b).

Another critical focus is the inclusivity of STEM education. Underrepresented groups—due to socio-economic factors, gender biases, or geographical inequalities—risk being excluded from meaningful engagement with STEM. Future efforts should emphasize culturally responsive pedagogies and equity-oriented reforms to ensure that STEM education fulfills its promise as an engine for innovation, social progress, and individual empowerment (Susilo & Sudrajat, 2020).

By synthesizing core learning theories with contemporary teaching approaches, educators can offer robust, student-centered learning experiences that mirror the complexities and collaborative nature of modern science, technology, engineering, and mathematics. These approaches—grounded in research and refined through practice—enable learners not just to retain knowledge but to evolve into agile thinkers, innovative problem-solvers, and conscientious citizens equipped for the global challenges that lie ahead.

Future research might investigate the relative effectiveness of specific theory-driven interventions across different grade levels, cultural contexts, and STEM domains. Longitudinal studies on how students transition from secondary STEM programs to higher education or STEM-related careers could provide more nuanced insight into the long-term impact of these instructional strategies (Gavrilas et al., 2022). Regardless of the method or theory emphasized, a consistent message emerges from the evidence: STEM education can unlock its full transformative potential when grounded in solid theoretical foundations and enacted through pedagogical practices that actively engage learners in investigating, questioning, and co-constructing knowledge in meaningful contexts.

Author contributions: Both authors contributed to the conception, design, data collection, interpretation, writing, and critical revision of the article. Both authors approved the final version of the article.

Funding: The authors received no financial support for the research and/or authorship of this article.

Ethics declaration: This study does not require any ethical approval or informed consent because it reviews existing literature and does not involve new data collection from human participants.

Declaration of interest: Authors declare no competing interest.

Data availability: Data generated or analyzed during this study are available from the authors on request.

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