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Teachers as facilitators and innovators in 21st-century STEM education

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ABSTRACT
This integrative review examines how teachers function as facilitators and innovators in integrated science, technology, engineering, and mathematics (STEM) across early childhood, primary, and secondary schooling and identifies the conditions that enable sustained practice using Greece as an illustrative centralized context. Guided by constructivist sociocultural and communities of practice perspectives, we reviewed peer-reviewed studies and key policy and curriculum documents published from 2010 to 2025, together with earlier foundational works. Sources were coded into teacher roles and enabling conditions and synthesized narratively. We find eight recurring roles that characterize effective STEM teaching, including the shift from transmission to facilitation, the design of authentic and context-rich problems, the scaffolding of inquiry, purposeful integration of technology, cultivation of a growth mindset, sustained professional learning, a commitment to equity and inclusion, and partnership brokering with families, industry, and communities. Enabling conditions include alignment among curriculum, instruction, and assessment, protected collaboration time, and supportive leadership and policy, including rules on teacher assignment. Illustrative enactments include play-based robotics in early childhood data-rich projects in primary classrooms and interdisciplinary co-taught design challenges in secondary settings. Persistent tensions involve crowded timetables, limited moderation of common performance tasks, and technology used as an add-on. We outline system-level levers such as moderated common tasks, professional learning communities, protected time for planning, and clearer policy to practice bridges that can help translate integrated STEM from aspiration to routine classroom practice.

Keywords: integrated STEM education, teacher roles, inquiry-based learning, curriculum alignment, professional learning communities, centralized education systems

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INTRODUCTION

Rationale and Overview

The teacher's role in science, technology, engineering, and mathematics (STEM) education has expanded beyond the conventional task of transmitting disciplinary knowledge. As STEM approaches gain momentum in contemporary schooling, educators are positioned to foster student autonomy, inquiry, and problem-solving skills (Darling-Hammond et al., 2020; Fullan, 2013; Gavrilas & Kotsis, 2024; OECD, 2018). This shift arises from the recognition that 21st-century learners must not only master scientific and mathematical concepts but also develop critical thinking, collaboration, and creativity to address complex challenges in a rapidly changing world. Integrated STEM emphasizes inquiry, design, and explicit connections among disciplines and is associated with gains in problem-solving and conceptual understanding when assessment and instruction are coherent (English, 2017; Gavrilas et al., 2024; Kelley & Knowles, 2016; National Research Council, 2012; Roehrig et al., 2021a; Tytler et al., 2019).

In this context, teachers are called to facilitate learning rather than deliver information. They guide students in applying scientific methods, formulating hypotheses, analyzing data, and linking abstract concepts to everyday life (Gavrilas & Kotsis, 2025a). Moreover, the STEM framework encourages the purposeful integration of technology, collaborative projects, and problem-based activities that support active participation (Kotsis, 2025). Although these strategies can yield profound benefits, such as deeper conceptual understanding and heightened engagement, they require careful scaffolding, ongoing professional development, and supportive school structures (Freeman et al., 2014; Furtak et al., 2012; Theobald et al., 2020).

This paper examines the teacher's responsibilities in STEM across levels, from preschool to secondary school. It explores how educators transition from teacher-centered approaches to facilitative methods and discusses the implications for curriculum design, professional growth, and inclusive practices. The analysis considers national policy frameworks, the role of teacher specializations, and various models of community collaboration, highlighting challenges and opportunities documented in inquiry- and problem-based research.

Theoretical Framing

Our synthesis is informed by constructivist views of learning, in which understanding is built through active engagement with problems and explanations, by sociocultural accounts that highlight learning as participation in shared practices with guidance and tools, and by communities-of-practice perspectives on how teachers develop expertise through collective work overtime (Bruner, 1996; Lave & Wenger, 1991; National Research Council, 2000b; Vygotsky, 1978; Wenger, 1998). Within this view, the teacher's role as facilitator involves scaffolding inquiry and design so that students connect ideas across disciplines and take increasing responsibility for strategy use and explanation (Bybee, 2013; Wood et al., 1976). The enablers in our framework align with this lens since curriculum and assessment coherence, professional learning, collaboration time, and partnerships create the conditions for teachers to enact these practices consistently (Kelley & Knowles, 2016; Roehrig et al., 2021a; Tytler et al., 2023).

Research Gap and Contribution

While prior work examines STEM pedagogy, technology integration, teacher professional development, equity, and partnerships, these strands are often treated separately and at a single schooling stage. Reviews repeatedly flag persistent subject silos and challenges achieving integration across disciplines (Arshad & Al, 2021; Roehrig et al., 2021b; Tytler et al., 2019, 2023). Empirical and review work also tends to concentrate on one level at a time, for example, early childhood or primary implementations, or secondary reforms, rather than tracing how teacher roles evolve across stages (English, 2017; Estapa & Tank, 2017; Gavrilas & Kotsis, 2025c; Wan et al., 2021, 2023). In centralized systems such as Greece, feasibility is further shaped by curriculum frameworks and teacher specialization/assignment practices, yet these system levers are seldom connected explicitly to day-to-day pedagogy in the literature (DeCoito, 2024; Roberts & Roberts, 2023; Gavrilas & Kotsis, 2025d; Papanikolaou et al., 2021).

This article consolidates a cross-level view of STEM teachers' roles, foregrounding facilitation of inquiry, orchestration of interdisciplinary and technology, rich learning, attention to inclusion, and brokering of community partnerships, while addressing fragmentation identified in reviews on coherence and integration (Roehrig et al., 2021b; Tytler et al., 2019). We make explicit how enactment depends on assessment–curriculum alignment (Hsu & Fang, 2019) and sustained professional development (Surahman & Wang, 2023), supported by protected collaboration time. In centralized contexts such as Greece, we add a policy-to-practice bridge by linking teacher-assignment rules and curriculum frameworks to feasible patterns of implementation (Roberts & Roberts, 2023; Gavrilas et al., 2024). Finally, we ground the synthesis in level-appropriate exemplars, from early childhood (e.g., robotics/play-based inquiry) through primary (project-based learning with coding) to secondary (multi-teacher design challenges), to illustrate how roles translate into teachable routines (Sullivan & Bers, 2016; Wan et al., 2023).

Approach (Objectives, Scope, and Method)

This article has three objectives: to identify recurring teacher roles that support integrated STEM across early childhood, primary, and secondary and to describe how enactment changes with learner development, to link enactment to enabling conditions in centralized systems so that classroom routines connect with assessment and curriculum, professional learning, collaboration time, and partnerships/policy, and to illustrate enactment with brief classroom examples at each level.

International examples are illustrative rather than prescriptive. Greece is used as a case of a centralized system to show how teacher-assignment rules, curriculum frameworks, and partnerships shape feasibility. The core claim that teacher roles are sustained by assessment and curriculum alignment, professional learning, collaboration time, and partnerships is broadly transferable, while implementation details are context-dependent and require local adaptation (OECD, 2018).

We conducted an integrative conceptual review to map teacher roles and enabling conditions for integrated STEM. Searches were run in ERIC, Scopus, Web of Science, and Google Scholar using terms related to integrated STEM, inquiry, design, technology integration, teacher role, professional development, assessment, equity, collaboration, and policy. We included peer-reviewed studies and authoritative curriculum or policy documents in school settings and excluded tertiary-only contexts, single-discipline studies without integration, and sources not in English unless directly relevant to Greece. The window was from 2010 to December 2024, with earlier works for foundational definitions. Sources were coded into role and enabler categories and synthesized narratively. This is an integrative review, not a systematic review, and we do not claim completeness.

Organizing Schema: Roles, Levels, and Enablers

Rather than proposing a new framework, we organize the review around three dimensions that are well established in the integrated STEM literature: what teachers do (roles), where enactment occurs (levels across early childhood, primary, and secondary), and what makes enactment feasible (enablers). This organizing schema is informed by scholarship that argues for intentional cross-disciplinary design and curricular coherence (Kelley & Knowles, 2016; Roehrig et al., 2021b; Tytler et al., 2023). Eight recurring roles structure the discussion: evolving from traditional instruction to facilitating learning; creating practical learning experiences; emphasizing inquiry-based learning; integrating technology in STEM teaching; cultivating a growth mindset; continuous professional development (CPD); promoting equity and inclusion; and community collaboration. We trace these roles across levels so that enactment is developmentally appropriate and vertically aligned, consistent with evidence that effective integration depends on deliberate collaboration among teachers across subjects and years (Wang et al., 2020).

Enablers denote the conditions that sustain enactment: assessment and curriculum alignment that values design-based reasoning; sustained professional development (often via professional learning communities [PLCs]); protected collaboration time for cross-specialty planning; and partnerships and policy levers, such as school–industry links and teacher-assignment rules, including resourcing and infrastructure, that connect classroom work to community and system priorities (Harris et al., 2023; Liu et al., 2024; Pattison, 2021; South Australia Department for Education, 2018; Surahman & Wang, 2023). An overview appears in **Figure 1** and **Table 1**. Subsequent sections unpack each role and show how enactment varies by level while keeping enablers in view.

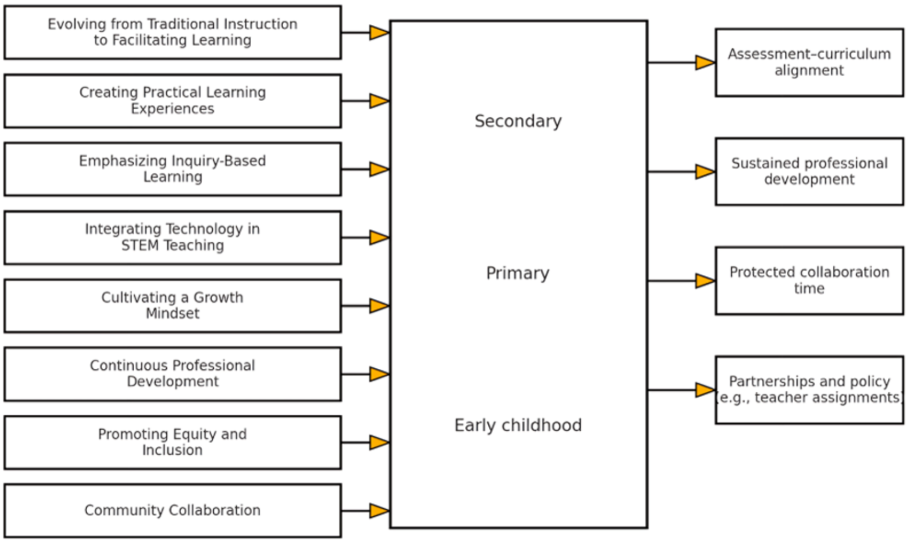

Figure 1. Organizing schema for the review: Roles, levels, and enablers in integrated STEM (Source: Authors' own elaboration)

Table 1. Summary of eight roles with examples and key enablers across schooling levels

Manuscript subheading	Early childhood example	Primary example	Secondary example	Key enablers
Evolving from traditional instruction to facilitating learning	Teacher models facilitation moves during play-based inquiry; children plan, test, and revise.	PBL unit with teams designing fair tests while the teacher coaches.	Co-taught design challenge with explicit criteria and reflection routines.	Assessment aligned with inquiry and design; time for planning and feedback.
Creating practical learning experiences	Hands-on stations connecting science ideas to everyday tools and materials.	Local data collection and analysis linked to community questions, using simple sensors where feasible.	Authentic briefs from community partners guide projects with evidence-based decisions.	Access to materials and community contexts; partnerships and safety procedures.
Emphasizing inquiry-based learning	Open questions, observation journals, and talk moves that elicit predictions and explanations.	Student-planned investigations that connect mathematics with science ideas, including data displays.	Design of experiments and model-based reasoning with peer critique.	Inquiry targets in rubrics; collaboration time to plan investigations.
Integrating technology in STEM teaching	Story-based robotics and simple coding are linked to early mathematics and spatial ideas.	Block-based programming or microcontrollers can be used to visualize data and automate measurements.	CAD, simulation, data logging, and coding are integrated with science and mathematics.	Devices and software matched to goals; professional development on pedagogy with technology.
Cultivating a growth mindset	Process praise and "yet" language with reflection on strategies.	Peer and teacher feedback cycles that celebrate iteration and incremental gains.	Structured design reviews focusing on criteria, evidence, and revision plans.	Shared rubrics that value process; mentoring for formative feedback.
CPD	Coached a lesson study on inquiry centers and played engineering tasks.	Professional learning communities that co-plan PBL, coding, or robotics.	Cross-specialty communities of practice and practitioner mentoring.	Scheduled collaboration time, leadership support, and sustained professional development.
Promoting equity and inclusion	Multilingual support and examples that reflect children's experiences.	UDL options, varied products, and mixed-ability grouping with targeted scaffolds.	Low-floor, high-ceiling briefs with multiple ways to demonstrate understanding.	Inclusive assessment practices, resources, and partnerships that support access.
Community collaboration	Family mini-projects on local themes.	Citizen-science or local problem briefs with simple data collection.	Industry-linked capstones or mentoring on authentic briefs.	Agreements with partners, time for visits, and safety policies.

THE MULTIFACETED ROLE OF THE STEM EDUCATOR

Evolving from Traditional Instruction to Facilitating Learning

STEM education rests on active, inquiry-based models that engage students with real-world problems through collaborative projects, design challenges, and problem solving; meta-analytic evidence shows active learning outperforms traditional lecturing in STEM on achievement and failure rates (Freeman et al., 2014; Furtak et al., 2012; Lazonder & Harmsen, 2016). Accordingly, teachers move from lecture-driven transmission toward a facilitative role. Integrated STEM frameworks and empirical syntheses articulate what this facilitation involves and why it improves outcomes, and practice-oriented overviews echo the same shift in school settings (Dacumos, 2023; English, 2017; Kelley & Knowles, 2016; Roehrig et al., 2021b). In this view, facilitation means designing for coherence by intentionally connecting disciplinary ideas through authentic problems and engineering design rather than presenting isolated facts. This transition also requires scaffolding inquiry and project-based learning and aligning instruction and assessment so that investigation, design, and explanation are valued (Bybee, 2013; National Research Council, 2012).

Assessment in integrated STEM works best when it mirrors inquiry and design. Formatively, teachers elicit student ideas in talk, use brief checks for understanding, and provide task and process-focused feedback that guides next steps (Hattie & Timperley, 2007; Shute, 2008; Wisniewski et al., 2020). In sum, students compile portfolios of investigations and design artifacts, and common performance tasks with moderation support comparability across classes (English, 2017; Gao et al., 2020; Hsu & Fang, 2019; National Research Council, 2012; Roehrig et al., 2021a). When assessment and instruction are aligned in this way, active and inquiry-oriented approaches are more likely to yield gains in engagement and understanding (Freeman et al., 2014; Furtak et al., 2012; Theobald et al., 2020).

A central responsibility within this facilitative stance is to make interdisciplinary connections explicit. Teachers design and orchestrate curricula that combine STEM into cohesive experiences, helping students see interdependence and apply interdisciplinary reasoning in areas such as environmental science, robotics, and data analytics (Daugherty & Carter, 2018; Kelley & Knowles, 2016; Mayes & Rittschof, 2021). This work involves selecting relevant projects, mapping content standards, and showing how scientific principles intersect with mathematical modelling and technological development, often in collaboration with colleagues across departments so that the school culture supports integrated activity (Gao et al., 2020; Kotsis, 2025; Madden et al., 2013). Teachers create space for students to question, hypothesize, test, and iterate even when work departs from textbook sequences, and they coordinate across specialties to sustain integration over time (Wang et al., 2020). Research and syntheses indicate that these approaches foster engagement and deeper understanding and help develop the collaborative mindset needed for contemporary societal challenges (Capraro & Slough, 2013; Freeman et al., 2014; Gavrilas et al., 2025; Kennedy & Odell, 2014).

Creating Practical Learning Experiences

STEM education seeks to move beyond theoretical knowledge toward experiences grounded in authentic tasks. Teachers, therefore, design and implement activities that simulate real-life scenarios, prompting students to apply classroom concepts to tangible challenges (Gya & Bjune, 2021; Su & Chen, 2023; Tsakeni, 2022). For instance, an instructor might organize a design challenge where students develop a simple machine to solve a specific community need, integrating mechanical principles, mathematical calculations, and iterative testing.

These experiential strategies encourage students to behave like researchers or innovators, formulate questions, gather data, and engage in collaborative teamwork (Papanikolaou et al., 2023). Practical tasks enhance creativity, deepen conceptual understanding, and instill important soft skills such as communication and adaptability (Campbell et al., 2018; Lin et al., 2020). By fostering these skills, teachers better prepare students for fast-evolving professional contexts, reinforcing the critical notion that STEM knowledge holds direct applicability in diverse, real-world settings.

Emphasizing Inquiry-Based Learning

Inquiry-based learning forms a core methodology in STEM education, providing a learner-centered framework that encourages exploration and autonomous knowledge construction (National Research Council, 2000a). Teachers guide students through scientific processes–such as formulating hypotheses, designing and executing experiments, interpreting data, and drawing conclusions–while gradually reducing direct support as learners gain competence (Abdurrahman et al., 2019; Attard et al., 2021; Pedaste et al., 2015).

To operate inquiry-based instruction, educators adopt the stance of mentors rather than authoritative dispensers of facts. They model scientific thinking by asking open-ended questions, prompting students to reflect on their methods, and encouraging them to refine their investigative skills (Kotsis, 2025). This orientation aligns with actual scientific practice and fosters a culture where trial, error, and revision are natural components of meaningful learning (Ješková et al., 2022; Zahara et al., 2020). By adopting such strategies, teachers empower students to develop scientific literacy and critical reasoning, crucial aptitudes for active citizenship in increasingly complex social and technological environments (Gavrilas & Kotsis, 2025b).

Integrating Technology in STEM Teaching

Teachers are key facilitators of technology integration, leveraging digital tools to create interactive and personalized learning experiences (Chacko et al., 2015; Roopaei & Klaas, 2021). From simulation software and online collaboration platforms to coding activities and data analysis programs, technology extends the scope of learning beyond the physical constraints of the classroom. However, effective technology integration requires pedagogical expertise rather than mere technical proficiency. Instructors must design lessons beyond surface-level use of devices, steering students toward higher-order thinking and meaningful project work (Chiu & Li, 2023; Means et al., 2009).

Professional development remains a critical enabler of this shift, ensuring educators remain current with evolving technological tools and best practices (Nguyen et al., 2024; Nie, 2021; Triplett, 2023). Well-structured training helps teachers navigate digital resources responsibly, implement adaptive learning systems, and address digital equity issues. Teachers broaden students' exposure to the digital world by weaving technology into lesson plans, strengthening their computational thinking and problem-solving abilities (Papanikolaou et al., 2021).

Cultivating a Growth Mindset

A growth mindset, defined as the belief that abilities can be developed through dedication, effective strategies, and feedback, is associated with success in STEM learning. Teachers play a central role in shaping classroom cultures that encourage experimentation and resilience (Kramer et al., 2023; Limeri et al., 2020; Stohlmann, 2022). Rather than praising innate talent, educators highlight perseverance and strategy use, helping students view mistakes as valuable learning opportunities. Research shows that learners who adopt a growth mindset tend to display higher motivation, greater persistence when facing challenges, and better academic performance (Dweck, 2008). Teachers support these outcomes by giving timely tasks and process-focused formative feedback, modeling adaptive responses to difficulty, and acknowledging incremental gains. Contemporary practice literature underscores the importance of normalizing setbacks and praising effective strategies (McDaniel, 2024; Sousa & Clark, 2024; Suman, 2023). Empirical syntheses link such feedback to improved learning when it is specific and actionable (Hattie & Timperley, 2007; Shute, 2008; Wisniewski et al., 2020), and large-scale experimental work shows that framing mistakes as part of learning through growth mindset messaging can yield benefits in particular contexts (Yeager et al., 2019).

Continuous Professional Development

Given the rapid pace of change in science, technology, and engineering, CPD for teachers is crucial (Costa et al., 2022; Olatunbosun & Nwankwo, 2024; Surahman & Wang, 2023). Effective CPD programs keep educators abreast of emerging research, pedagogical strategies, and digital resources. Such programs foster a climate of lifelong learning, enabling teachers to adapt curricular content to current STEM developments and to refine the collaborative, inquiry-based methods that underpin transformative classroom experiences (Gardner et al., 2019; Gavrilas & Kotsis, 2025a; Kang, 2019).

Professional development should not be episodic but integrated into a teacher's career trajectory, featuring hands-on workshops, peer observations, and follow-up coaching. Thus, teachers have repeated opportunities to experiment with new approaches, gather feedback, and reassess their instructional techniques. Collaboration within PLCs can facilitate the sharing of best practices and the collective resolution of challenges, leading to a stronger, more cohesive STEM culture within the school.

Promoting Equity and Inclusion

Another critical responsibility of the STEM educator is to ensure that every student has access to meaningful, high-quality learning experiences. Teachers help identify and dismantle barriers–whether from socioeconomic disparities, cultural biases, or gender stereotypes–that can hinder student participation in STEM (Jones, 2016; Marshall et al., 2022; Palid et al., 2023). In practice, inclusive strategies range from differentiating instruction for diverse learning needs to selecting culturally responsive content that resonates with students' backgrounds.

Research suggests that such inclusive practices can help narrow achievement gaps and encourage underrepresented groups to pursue STEM pathways (Fisher et al., 2024). Teachers cultivate an environment that celebrates diversity and frames challenges as opportunities for collective growth. By acknowledging students' varied perspectives and fostering respect, instructors nurture a learning community where all learners feel valued and empowered. This cultural shift is indispensable for developing a broader, more innovative future workforce (Gontas et al., 2021; Marshall et al., 2022).

Community Collaboration

Collaboration with external stakeholders–local businesses, universities, research institutes, and nonprofit organizations–brings authentic problem-solving opportunities into the classroom (Foster et al., 2010; Gilbert et al., 2020; Kleinschmit et al., 2023). Teachers proactively identify potential partners, devise joint projects, and guide students to tackle context-specific or industry-related challenges. Such partnerships illuminate how classroom lessons map onto the realities of professional engineering, science labs, or entrepreneurial ventures (Burrows et al., 2018; Hite et al., 2020).

Community collaboration also benefits educators by enhancing their professional networks and subject knowledge. Exposure to cutting-edge research or emerging industrial trends fosters a deeper understanding of adjusting classroom activities to reflect workplace practices (Kleinschmit et al., 2023; May & Lopez, 2020). By bridging academic and community settings, teachers cultivate student engagement, bolster career awareness, and promote the idea that STEM competencies are directly relevant to addressing social and economic challenges.

STEM EDUCATION ACROSS DIFFERENT SCHOOL LEVELS

Overview of STEM Implementation in Schools

STEM education spans all stages of formal schooling, from early childhood through secondary education, although its structure and emphasis vary according to developmental considerations and curricular frameworks. Common to all levels is the aim of cultivating 21st-century competencies such as critical thinking, problem-solving, collaboration, and innovation (Papanikolaou et al., 2021). The interdisciplinary nature of STEM encourages students to integrate knowledge from multiple domains, thus forming a solid foundation for further academic pursuits and career readiness.

In the early years, child-centered exploration of fundamental scientific and technological principles lays a foundation for curiosity and positive attitudes toward learning. Teachers reinforce these skills in primary school by introducing students to more systematic scientific inquiry and mathematical concepts while integrating playful or hands-on learning methods. Secondary education builds on these foundations with deeper disciplinary content and an expanded focus on advanced topics and career exploration (English, 2017; Estapa & Tank, 2017).

STEM in Early Childhood Education

In many education systems, STEM approaches are advocated even at the preschool level, and research suggests that young children show a natural inclination for inquiry, experimentation, and collaborative problem solving (Stone-MacDonald et al., 2011). This stage is widely recognized as critical for brain development, and early exposure to STEM is associated with later academic trajectories (Chesloff, 2013; Kermani & Aldemir, 2015). Play-based and inquiry-driven activities that combine science concepts with technology or mathematics are increasingly used to stimulate children's curiosity and to cultivate a positive orientation toward STEM (Mantzicopoulos et al., 2009).

Children work in pairs to program a small floor robot to reach a pretend animal habitat on a classroom map. The teacher invites students to plan, test, and revise paths and to explain why a sequence of commands succeeded or failed. Counting steps connects to early mathematics, and the discussion of position and turn connects to spatial reasoning. Autonomy is supported through choice of routes and materials, and inquiry is facilitated through open questions and shared reflection. Studies report gains when early robotics and play are used to structure inquiry and agency in the early years (English, 2017; Sullivan & Bers, 2016).

International examples underscore the viability of STEM programs for preschoolers, including initiatives that use technological tools or simple robotics kits to help children work cooperatively and tackle complex tasks (Bagiati & Evangelou, 2016; Sullivan & Bers, 2016). Even when STEM is not explicitly named, curricular flexibility allows educators to incorporate cross-disciplinary, hands-on learning. Teachers facilitate experimentation, encourage questions, and help children see scientific inquiry as accessible and rewarding (Wan et al., 2021; Wan et al., 2023).

STEM in Primary Education

Within STEM, students engage with more structured tasks and experiments that build on the inquisitiveness nurtured in preschool. This development is supported by interactive methods such as small-scale projects, games, and digital tools, which provide opportunities for experiential learning (English, 2017; Estapa & Tank, 2017; Wan et al., 2023).

Students investigate shade and temperature around the school grounds. Teams propose a plan for measurement, collect data at different times of day, and use block-based programming to organize and visualize results. The teacher makes criteria and constraints visible and helps students link mathematics with science ideas about energy and materials. Teams propose solutions such as planting or simple shelters and justify choices with their data. Integration is strengthened when inquiry goals and assessment targets are aligned and when projects make the science and mathematics connections explicit (Capraro & Slough, 2013; Estapa & Tank, 2017; Hsu & Fang, 2019).

Problem solving is a central feature as teachers challenge students to apply mathematics, scientific thinking, and introductory engineering design in contexts that mirror everyday life (Jones et al., 2024). Technology integration becomes more pronounced as students learn basic computing skills, use tablets or educational software, and sometimes experiment with simple robotics kits (Barakat, 2022; Geiger et al., 2023). Project-based learning gains traction at this level, underscoring collaborative efforts and applied outcomes. In effect, primary STEM education aims to balance conceptual knowledge and hands-on practice, positioning students for more advanced topics in later grades (Geiger et al., 2023; Wan et al., 2023).

STEM in Secondary Education

During secondary education, STEM initiatives become more advanced and present students with in-depth scientific topics and more sophisticated engineering and technology experiences. The aim is to cultivate cognitive abilities in science and mathematics along with broader capacities such as leadership, teamwork, communication, and autonomous learning (English, 2017; Kaleva et al., 2019). Curriculum frameworks encourage teachers to combine laboratory exercises, project-based tasks, and problem-solving scenarios that deepen conceptual understanding and reinforce the real-world relevance of academic content (Geesa et al., 2020; Imad et al., 2023). In practice, these cross-curricular design challenge units are frequently co-planned and co-taught by teachers from different specialties such as physics and computer science, aligning disciplinary rigor with integrative project outcomes (Wang et al., 2020).

Physics and computing teachers guide a community brief to design a sensor and display that warns of slippery surfaces near the school entrance. Student teams select designs, test prototypes, and explain tradeoffs based on evidence. Teachers facilitate questions and peer critique and align assessments with explanations, models, and design performance. The example shows interdisciplinary coherence and growing autonomy as students justify design choices with data. Research highlights the value of structured collaboration among subject specialists and coherent design across subjects for successful integration (Lin et al., 2020; Roehrig et al., 2021b; Wang et al., 2020).

Teachers also encourage students to develop a habit of continuous inquiry that connects classroom theory to current societal and technological developments. As students refine their critical thinking skills, they are prepared to pursue further study in STEM-related fields and to transfer these competencies to diverse career paths (Roberts & Roberts, 2023; Kotsis & Gavrilas, 2025; Tytler et al., 2023). By bridging disciplinary knowledge, practical application, and personal growth, secondary-level STEM education supports the development of scientifically literate and innovative citizens who can adapt to the uncertain landscapes of modern work and life.

Specialized STEM Teachers in Secondary Education

Secondary-level STEM instruction often involves a team of specialized educators in mathematics, physics, computer science, and chemistry. Each specialist contributes subject-matter expertise while participating in interdisciplinary collaborations that exemplify the core principles of STEM. For example, mathematics teachers move beyond presenting algebraic techniques to help students see how mathematical modeling informs engineering projects and physical computations (Alrwaished, 2024; Goos et al., 2023; Rahman et al., 2021). Physicists, for their part, mentor students in laboratory settings, introducing them to the processes of hypothesis testing, measurement, and data interpretation (Guan et al., 2020; Sulaeman et al., 2022). Computer science teachers teach programming, software development, and computational thinking, encouraging students to tackle real-world problems through digital innovation (Dorotea et al., 2021; Ottenbreit-Leftwich et al., 2022). Meanwhile, chemistry teachers deepen their understanding of matter, reactions, and applied research, often linking chemical principles to bioengineering or environmental initiatives (Hazzan & Ragonis, 2014; Newton et al., 2023).

Effective STEM instruction hinges on collaborative planning among these specialists, ensuring that projects and problem sets reflect genuine interdisciplinarity. Mathematics or physics teachers might coordinate with computer science colleagues to incorporate coding tasks into exploring dynamic systems. Chemistry and physics instructors can join forces to highlight the principles of energy, thermodynamics, and chemical reactions. Such cross-curricular activities also reveal to students that scientific concepts rarely exist in isolation. By addressing real-life phenomena, teachers reinforce the cooperation between theoretical understanding and its multifaceted applications (Anderson & Makar, 2024; Çelik Kaya & Akyüz, 2024).

CURRICULUM DESIGN AND TEACHER ASSIGNMENTS IN STEM

Teacher Assignments in Greek Secondary Education

Teacher assignments are governed by policies that align educators' qualifications and specializations with the subjects they are permitted to teach. The Ministry of Education issues guidelines specifying first and second teaching assignments, thereby regulating which courses a single teacher can handle. This mechanism ensures that educators with degrees in mathematics, physics, chemistry, or informatics, for instance, are primarily assigned to the subjects for which they possess the most substantial academic background. However, they may also teach closely related courses if needed.

Such assignments are critical for sustaining the quality and continuity of STEM education. By matching expert teachers to relevant subjects, students benefit from specialized knowledge and more precise explanations of complex scientific phenomena (Roberts & Roberts, 2023). The system also balances the distribution of educational resources across different regions, mitigating teacher shortages in remote areas. In the context of STEM, these assignment policies help maintain a robust instructional foundation as students interact with highly qualified professionals who connect domain expertise to problem-based activities.

Nonetheless, teacher assignments alone cannot solve interdisciplinary coherence or project-based integration issues. Recognizing that STEM involves multiple fields, policymakers and school leaders encourage teacher collaboration (Kotsis, 2025). Educators are thus expected to develop a deeper understanding of related disciplines and to coordinate with colleagues on cross-curricular units. CPD can help teachers expand their skill sets, offering them practical tools to manage overlapping content areas (Kleinschmit et al., 2023).

STEM Curriculum Frameworks and Policy

The effectiveness of STEM curricula depends heavily on robust design, strategic alignment with educational standards, and practical implementation. Policymakers collaborate with curriculum specialists, educational researchers, and teachers to create documents that guide instruction and specify learning objectives across grade levels (Gavrilas et al., 2024). These frameworks aim to develop an interdisciplinary structure without relegating engineering or technology to secondary status. However, in many systems, including Greece's, subject-specific traditions can sometimes complicate attempts at holistic reform (Arshad et al., 2021; Tytler et al., 2023).

Challenges often arise from a lack of clarity in how discrete fields should intersect or a scarcity of time within the timetable for sustained project-based work. Teachers may encounter organizational roadblocks, insufficient access to appropriate resources, or tensions with high-stakes assessments prioritizing rote memorization over creative problem-solving (Gavrilas & Kotsis, 2024). Despite these barriers, international comparisons suggest that well-structured STEM curricula, professional development, and external partnerships can transform educational experiences and outcomes (DeCoito, 2024; Roehrig et al., 2021b).

Strategies for Advancing STEM Curriculum

Effective STEM curriculum design relies on a handful of key strategies. One involves explicitly integrating engineering design tasks into science and mathematics courses, thus reinforcing the applied dimension of theoretical concepts (Ragan et al., 2021). Another essential strategy is providing teachers with the necessary support for delivering cohesive, interdisciplinary lessons, including training programs, co-planning sessions, and resource banks that offer exemplary lessons (Kazemnia et al., 2023). School administrators and policymakers also encourage collaborative networks with universities, local industries, and research institutes, which can supply professional expertise, host workshops, or provide authentic case studies for students to examine (Gavrilas & Kotsis, 2025b).

International models underscore the importance of ensuring that STEM curricula remain flexible enough to accommodate local context yet structured enough to promote consistent learning outcomes across regions. When combined with reflective assessments that value content knowledge and problem-solving abilities, STEM curricula can reshape educational culture, making real-world relevance a central criterion for measuring success (Hsu & Fang, 2019).

Challenges and Opportunities in STEM Curriculum Improvement

Despite ongoing reforms, significant hurdles impede the seamless integration of STEM at all educational levels (Tytler et al., 2019). Traditional subject compartmentalization persists, and teacher preparation programs may not fully reflect interdisciplinary imperatives, leaving educators underprepared to foster integrated learning. A gap frequently emerges between policy aspirations and classroom realities, especially when standardized tests prioritize narrow content mastery over holistic or creative competencies (Chomphuphra et al., 2019).

However, these challenges coincide with substantial opportunities. Growing recognition of STEM education's economic and societal value can fuel innovation and resource investment. Policymakers, educators, and industry partners increasingly value project-based learning, computational thinking, and design-based engineering tasks that sharpen students' 21st-century skills (Aslam et al., 2023; Roehrig et al., 2021b). By supporting professional development, expanding partnerships, and systematically evaluating curriculum implementations, education systems can progressively align STEM learning objectives with broader student needs, laying the groundwork for a more interconnected, dynamic, and inclusive approach to teaching and learning (Hsu & Fang, 2019; Tytler et al., 2023). Taken together, these roles and enablers suggest system-level levers and open questions, which we synthesize in the discussion.

DISCUSSION

Across levels, the literature converges on a facilitative teacher role and on integration where technology serves disciplinary reasoning rather than standing apart. When assessment and curriculum are aligned and teachers have sustained professional learning collaboration time and partnerships, inquiry and design are more likely to produce durable understanding and participation (English, 2017; Hsu & Fang, 2019; Kelley & Knowles, 2016; National Research Council, 2012; Roehrig et al., 2021b; Tytler et al., 2023).

At the same time, several tensions remain. In centralized systems, assessment regimes and timetables can constrain integration even when teachers are willing, and technology can drift into add-on use without shared planning and coherent tasks (English, 2017; Wang et al., 2020). Evidence on growth mindset shows promise but varies by context and implementation, which underscores the need for feedback practices that focus on process and evidence (Hattie & Timperley, 2007; Wisniewski et al., 2020; Yeager et al., 2019). Policy and leadership can address these tensions by providing shared performance tasks with moderation, protected collaboration time, and PLCs that sustain cross-subject design and assessment. Future work should examine longitudinal enactment across levels, develop reliable measures of integrated reasoning, and compare implementation under different teacher assignment rules and curriculum frameworks (Harris et al., 2023; Roehrig et al., 2021b; Tytler et al., 2023).

CONCLUSION

Teachers lie at the nexus of successful STEM education, acting as mentors, facilitators, innovators, and champions of equitable learning.

Their responsibilities are multifaceted, encompassing a shift from rigid instruction to strategies that encourage inquiry, creativity, and the practical application of knowledge. By integrating disciplines and exposing students to hands-on challenges, teachers make STEM engaging and relevant, enabling learners to tackle complex issues that cross-subject problems. These pedagogical transformations, however, necessitate strong institutional support, CPD, and collaborative communities of practice that help teachers refine their methods and remain current with emerging trends.

Throughout the various levels of schooling, from preschool to secondary education, STEM educators undertake a common mission: to demonstrate how STEM interlock to shape modern society and to cultivate the competencies students will need in a world rapidly disrupted by technological advancement. Play-based and inquiry-oriented tasks in early childhood spark curiosity and establish positive attitudes toward science and mathematics. Primary schooling deepens these experiences, weaving problem-solving and technological literacy into diverse projects. In secondary education, specialized teachers provide advanced content knowledge yet must also engage in cross-curricular planning to highlight the interconnected nature of their disciplines.

The careful design of STEM curricula and clear teacher assignments form a supportive scaffold for these efforts. By designating specialized educators in mathematics, physics, computer science, and chemistry, educational systems ensure that learners receive expert guidance. Simultaneously, policymakers strive to unify these fields within integrated curricula, thus acknowledging that real-world challenges demand the synthesis of multiple bodies of knowledge. While the gap between curricular ideals and on-the-ground realities may remain, systematic strategies, such as coherent professional development, interdisciplinary projects, and industry alliances, show promise for bridging the divide and enhancing student outcomes.

Embracing inclusion and equity is indispensable for unlocking STEM's full potential as a vehicle of personal and societal progress. Teachers foster an environment where students can thrive, explore, and aspire toward STEM fields by recognizing and supporting diverse learners. Ultimately, the teacher's role transcends rote instruction and textbook coverage; it is about cultivating a learning culture in which curiosity flourishes, resilience is nurtured, and critical thinking is ingrained as a lifelong attribute. As we look to the future, educators who are equipped, empowered, and validated in their evolving roles will remain pivotal to shaping the innovators, problem-solvers, and informed citizens of tomorrow's interconnected world.

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