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Communication technologies in STEM education: A systematic review

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Abstract
classrooms, yet evidence on their collective impact remains scattered across single-tool case studies. This systematic review closes that gap by analyzing nineteen empirical investigations published between 2020 and 2025 that deploy learning-management systems, mobile applications, extended reality (XR) environments and artificial-intelligence tutors in K-12 and tertiary science, technology, engineering, and mathematics (STEM) settings. Using a mixed method comparative synthesis, the study maps how these tools converge into integrated communication ecosystems and how their orchestration shapes conceptual understanding, collaboration dynamics and equity of access. The findings show that learning-management platforms and mobile messaging now anchor almost three quarters of deployments, providing a backbone for scheduling, resource distribution and threaded dialogue that bridges classroom and home. When these platforms are paired with short, scaffolded XR sessions and real-time, artificial intelligence-driven feedback loops, learners achieve double-digit gains in spatial reasoning, problem-solving and motivation while low-performing students close achievement gaps by up to thirty per cent. The review also uncovers persistent barriers: bandwidth constraints, high hardware costs and limited teacher data literacy temper the transformative potential of these tools, particularly in rural and linguistically diverse contexts. By clustering technologies, pedagogical approaches and methodological choices into a single analytic matrix, the review offers the first holistic blueprint for designing inclusive, data-rich STEM ecosystems. However, methodological heterogeneity, study durations shorter than one school term and convenience sampling from high-connectivity regions limit generalizability and call for longitudinal, multi-site designs and living evidence reviews. Overall, the study argues that communication technologies will reach their full promise only when technical ingenuity is matched by pedagogical wisdom and structural commitment.

Keywords: communication technologies, STEM education, extended reality, artificial intelligence tutors, learning management systems

INTRODUCTION

The fields of science, technology, engineering, and mathematics (STEM) are the ones that are most directly responsible for new scientific discoveries and technological advances (UNESCO, 2023). STEM education is a way of teaching that combines these fields to solve problems in the real world instead of teaching them as separate subjects (Kelley & Knowles, 2016). Meta-analytic research shows that such integrated approaches make it easier for teachers to combine ideas from different subjects (Wu et al., 2024) and lead to medium- to large-scale improvements in student performance (Chen et al., 2025a).

The economic case for STEM education is strong. According to science & engineering indicators data,

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Contribution to the literature

- The study presents a comprehensive synthesis that transcends the fragmented nature of technology research in STEM education. Unlike traditional research's single-tool-focused approach, this study demonstrates how learning management systems, mobile applications, augmented reality, and artificial intelligence enable teachers to create integrated ecosystems. This "ecosystem perspective" proposes a new paradigm in the literature.
- The study develops an innovative approach that clusters technologies, pedagogical approaches, methodological choices, and equity factors within a single analytical matrix. This methodology establishes a replicable research framework for the field and serves as a model for future systematic review studies.
- The study addresses barriers such as bandwidth limitations, hardware costs, teacher data literacy gaps, and rural challenges as central elements of analysis. This approach strengthens the social justice perspective in technology-enhanced STEM education.
- The study presents a new skill categorization that goes beyond discipline-specific knowledge, showing how transferable and discipline-specific competencies come together in technology-supported STEM learning. This taxonomy demonstrates how critical thinking, collaboration, engineering design, and digital competencies are integrated, establishing a new standard for STEM education assessment frameworks.

STEM workers made up 24% of the US workforce in 2021 and earned a median salary nearly $19,000 more than their non-STEM counterparts (National Science Board, 2024). The World Economic Forum states that nine of the ten fastest growing job categories by 2029 will be STEM-intensive jobs, such as artificial intelligence (AI) specialists and renewable energy engineers (World Economic Forum, 2023). But not everyone who goes to school in STEM gets the same benefits. Markey et al. (2021) and Li et al. (2021) say that we need culturally sensitive teaching, early exposure, and inclusive curricula to get rid of these kinds of problems.

Almost every part of teaching and learning can now be done with digital tools like cloud collaboration suites, synchronous video conferencing, mobile apps, learning management systems (LMS), and immersive media like augmented reality (AR) or virtual reality (VR) (Haleem et al., 2022; Wang et al., 2022). Recent bibliometric data show that research on these tools has grown by more than 20% every year for the past ten years. This shows how important they are in teaching and learning (Alam et al., 2025). Comprehensive bibliometric analyses reveal that information and communication technologies (ICT)-related research in science education has expanded significantly, with 325 publications identified between 2008-2023, demonstrating 1,394 total citations and growing international collaboration patterns (Khairullina et al., 2023). Similarly, science communication research in STEM education shows substantial growth, with 175 studies published between 2000-2022, particularly accelerating after 2018 (Ishmuradova et al., 2023). Communication technologies in education are the digital channels, networks, and devices that allow multimodal information–text, audio, video, and data–to be created, stored, transmitted, and exchanged in both directions across time and space (UNESCO, 2023). Together, these systems increasingly support personalized feedback and adaptive learning. They include mobile group messaging, emergent AI-enhanced or immersive platforms, synchronous environments (like live Zoom classes), and asynchronous spaces (like Moodle discussion boards) (Kerimbayev et al., 2023; Wang et al., 2024).

While the existing literature demonstrates the potential of various communication technologies in STEM education, there is a lack of systematic understanding of how these technologies affect teacher-student and student-student interactions. This fragmentation is evident across both formal and informal learning contexts, with systematic reviews revealing that research on afterschool STEM programs predominantly employs qualitative and mixed methods approaches (40% each), suggesting a field still developing its methodological foundations (Sogut & Tasar, 2024). No systematic review was found that examined all the different communication technologies and their impact on STEM education. Tene et al.'s (2024) systematic review of 22 extended reality (XR) studies is an example of a study that only looks at certain sorts of technologies. Furthermore, how these technologies produce different outcomes in different STEM disciplines and which pedagogical approaches are most effective have not been adequately explored.

Communication technologies in STEM education–ranging from LMS and mobile messaging to XR environments and AI driven tutoring chatbots–have multiplied at a breathtaking pace. Yet the empirical evidence remains siloed: most studies examine a single tool, short intervention or isolated outcome, offering little insight into how these technologies interact as a communication ecosystem or how their orchestration reshapes conceptual understanding, collaboration and equity in STEM. This disconnect between the systemic reality of communication technologies in STEM and the piecemeal nature of current research constitutes the core gap this review seeks to bridge.

Recognizing this gap, the present study positions communication technologies–not hardware, curricula or general digital literacy–as the analytical lens through which to reevaluate STEM learning. By mapping nineteen recent investigations into a common framework that integrates pedagogical strategies, methodological approaches and access considerations, the review provides the field's consolidated picture of how communication technologies collectively influence learning trajectories. Accordingly, the guiding research question is: *How do integrated communication-technology ecosystems–combining learning-management platforms, mobile devices, XR tools and artificial-intelligence tutors–shape conceptual understanding, real-time feedback loops and equity outcomes in K-12 and tertiary STEM education?* In answering this question, the study aims to identify actionable design principles and policy levers that can amplify the transformative potential of communication technologies in STEM classrooms worldwide.

LITERATURE REVIEW

Emerging Technologies and Innovative Applications

Immersive and XR environments–spanning VR, AR, mixed reality, and the broader umbrella of XR–are transforming how abstract STEM concepts are taught and experienced (Zhang et al., 2024). These tools let students see things that are dangerous, too expensive, or just impossible to see in person by putting 3-D models, data, and simulations on top of the real world or putting students in fully simulated labs and field sites (Ahsan et al., 2025). Ruiz-Muñoz et al. (2024) did a quasi-experimental study with 180 college students and found that AR-enhanced instruction led to a 14.3-point improvement in performance compared to a traditional condition ($F[1, 177] = 38.24$, $p < 0.001$). This was also true for motivation and attitudes toward STEM (Ahsan et al., 2025). Meta-analytic evidence backs up VR's positive effects on factual, conceptual, and transfer learning outcomes (Cromley et al., 2023).

Virtual laboratories (VLs) and virtual robotics let users try out new skills, which makes XR even better. Bose and Humphreys (2022) discovered that Indian instructors who practiced in a VL were able to use what they had learned in a real lab more quickly ($p < 0.002$) and accurately ($p = 0.012$) than teachers who had not practiced in a VL. This illustrates that VLs can help you get better at both understanding and doing things (Li & Liang, 2024). Alsoliman's (2022) study of eighth graders also found that virtual robots can help pupils think critically and solve problems without the cost and upkeep of genuine kits.

These 22 XR studies' conclusions are backed up by a recent systematic review by Tene et al. (2024): In math, chemistry, biology, and engineering graphics, AR/VR always helped people comprehend things better, get more motivated, and work better as a team. For instance, Chonchaiya and Srithammee (2025) produced a mobile AR geometry software that boosted vocational students' test scores from 3.70 to 9.04 on a ten-point scale ($d = 2.05$) and also obtained a good score on the system usability scale (78.5). During the pandemic lockdowns in Thailand, researchers employed AR in the same way to keep students interested in classes on transformational geometry.

XR works well with gamification in addition to visualization. In a "digital communication" course, Zolezzi et al. (2024) put challenges and quizzes into EON-XR 360° scenes. Students said they learned more and were better prepared for exams than in regular classes. Researchers, on the other hand, say that XR should not be used just because it looks cool. It should be aligned with learning goals and supported by reflection and guidance.

Another new area is tutoring systems that use AI. Large language lodels and multimodal generative AI can now give adaptive feedback in K-12 math, physics, and computer science classes using text, voice, and images (Cosentino et al., 2025; Heilala et al., 2025; Nixon et al., 2024). Early classroom pilots show that students are more engaged and have more personalized paths to mastery. Innovations in the metaverse and elsewhere promise shared virtual worlds where people can work together to solve problems. In their study of blended courses, Singh and Sun (2025) found that activities based on Minecraft improved social presence and STEM outcomes. Digital society school These permanent spaces are home to virtual labs, engineering design challenges, and experiences that are open to everyone and based on their skills.

Effectiveness and Learning Outcomes

Recent studies show that when communication technologies are used in the right way with teaching methods, they can help students learn more in math, science, and technology. A meta-analysis of 3,894 students found that digital games were better than traditional teaching in general (ES = 0.667, 95% confidence interval [0.520-0.814]) (Wang et al., 2022). A study of immersive media in high school through graduate school found that VR apps had a positive average effect of $g = .33$ (Cromley et al., 2023). These results show that technology can help a lot of people do better, but they also show that the effect depends on how well the tool is used and how well it fits the learning goal.

The effectiveness of technology-enhanced STEM instruction is particularly pronounced when it incorporates engineering design as an integrator, as emphasized by Bryan and Guzey (2020). Their framework for integrated STEM education identifies five distinguishing elements: anchor disciplines that define primary learning goals, engineering practices as the integrator, design justification requirements, emphasis on 21st century skills development, and real-world problem-solving contexts through teamwork and communication. This pedagogical approach ensures that communication technologies serve not merely as digital novelties but as meaningful tools that facilitate authentic disciplinary integration and collaborative knowledge construction.

Immersive VR and AR environments usually assist individuals picture and retain abstract ideas, especially in science contexts where there are significant spatial relationships. Studies done in the classroom demonstrate that 15 to 30 minutes of desktop VR sessions had the best results without keeping the brain too busy (Cromley et al., 2023; Ruiz-Muñoz et al., 2024). Mobile devices are fantastic for helping children learn outside of school and obtain help and feedback when they need it. A thorough evaluation of the years 2014 to 2023 demonstrates that higher education has gotten better over time in terms of performance, engagement, and happiness (Kang, 2024). Karatay et al. (2024) say that experimental data suggests that animated simulations assist students understand topics better and feel more at ease using ICT. Video conferencing and computer-supported collaborative learning settings allow people work together when sessions are planned with breakout tasks. However, designers need to be careful with the pacing to avoid “Zoom fatigue” (Basch et al., 2025; Nadler, 2020). When used for peer mentoring or professional networking, social media channels are most useful. For example, studies of university students show that they are more likely to be interested in STEM and have a better attitude toward it when they use LinkedIn, YouTube, or Instagram to share and discuss content instead of just chatting (Alalwan, 2022). At the adaptive end of the spectrum, AI-driven precision-teaching systems find misconceptions in real time, raise average science scores, and close achievement gaps by directing low-performing students to targeted practice (Hao et al., 2024). Virtual and asynchronous labs also show strong “virtual-to-real” transfer: students who practiced experiments online did the same things faster and with fewer mistakes in real labs (Bose & Humphreys, 2022; Dao et al., 2024).

One of the main cognitive benefits of these technologies is that they make the invisible visible. When students use AR overlays, 3-D molecule viewers, and interactive mobile animations to help them build more complex mental models of orbital mechanics, vector fields, or micro-scale chemical processes, they do better on tests and remember what they learned better (Karatay et al., 2024; Ruiz-Muñoz et al., 2024). Gains in feelings are just as important. A lot of the time, students say that tech-based activities are “fun,” and studies show that motivation goes up when lessons are tailored to each student or are immersive (Hao et al., 2024). This kind of involvement makes people more interested in STEM fields and more determined, which are both important for long-term success.

In addition to learning the material, technology integration helps students learn skills they will need in the 21st century. Mobile and AR interventions make students feel more confident in their ICT skills, which helps them get ready for jobs that need a lot of technology (Karatay et al., 2024; Papanastasiou et al., 2019). People can really practice leadership, negotiation, and working together to solve problems on collaborative platforms. Virtual, project-based courses keep track of what happens in these activities (Fang et al., 2021; Freeman et al., 2022). Teachers can set up tools along a scaffolding continuum to help students learn both mastery and independence. They can start with AI tutors that give them a lot of help to build their confidence. Then they can work on team projects in CSCL spaces. Finally, they can do their own research in virtual labs (Zolezzi et al., 2024).

Digital assessment and learning analytics systems close the feedback loop and use data to measure progress. You can grade Python- or MATLAB-based quizzes right away and see what students are getting wrong in real time when you add them to engineering math modules. This lets you reteach them just in time (Cirneanu & Moldoveanu, 2024). Dashboards that show click-stream and performance data help teachers find students who are at risk and reach out to them in a way that works for them. Field studies show that students do much better when teachers use this kind of data (Okoye et al., 2024). Modern AI tutors make it even harder to tell the difference between assessment and instruction because they automatically give students extra work to do when they make mistakes (Li et al., 2023). Researchers say that for open-ended tasks, automated scoring should be used along with human review to make sure they are fair and correct. They also say that teachers need training in data literacy to use analytics responsibly (Ariely et al., 2023; Cirneanu & Moldoveanu, 2024).

Practical design choices are also important for effective deployment. When it comes to VR or long video meetings, the length of the session and the cognitive load must be balanced. Students with limited internet access or different ways of solving problems must have equal access to the same resources. Finally, it is very important to use learner data in an ethical way. When these things are considered, communication technologies don’t just add to the fun; they help students learn more deeply and broadly in STEM.

Critical Challenges and Barriers to Implementation

Although communication technologies in STEM education have proven to be effective, their widespread implementation faces many challenges. These challenges are seen in the technical, institutional, financial and pedagogical domains. The literature shows that these barriers stem from techno-structural, pedagogical and human factors.

The most fundamental problem is the digital divide. Lack of equal access to the necessary hardware and infrastructure creates equity issues in education. Technical barriers stand out as the primary problems. Especially schools in rural areas struggle due to inadequate infrastructure (Kormos & Wisdom, 2021). The high cost of devices such as smartphones, tablets and computers is a major problem for students and their families (Karatay et al., 2024). Students in regions with older technology have difficulties in STEM courses because they cannot access up-to-date software and digital tools.

Another big problem is how reliable technology is. All technology can break down, which can make it very hard to learn. Researchers say that technical problems are common. These include slow internet speeds that stop media from loading, power outages that happen without warning, and bugs in software or hardware that make things hard for students and teachers (Karatay et al., 2024; Ruiz-Muñoz et al., 2024). The way devices are built can also cause problems. For instance, the small screens on mobile phones can make it hard to read long texts or use complicated simulations (Karatay et al., 2024).

Cost factors make things very hard. Robotics kits, AI software, and IoT devices are some of the specialized tools that are needed for STEM education. Many schools can't afford these tools (Varghese et al., 2025). Problems become more complicated when institutions and organizations don't want to change. These are policy, management, and structural limits (Bećirović, 2023). Policies in institutions often make things harder than they need to be. Some of these are strict internet filtering and strict grading systems. Teachers say that limitations in the curriculum make it hard for STEM courses to be interdisciplinary. There are problems with the structure, like not enough administrative and financial support at the district level (Herro et al., 2019).

The most critical challenge is the human factor. This is particularly related to teacher and student preparedness. Teacher training needs are a critical barrier. Significant professional development is required for educators to effectively deliver technology-enabled STEM education (Öztürk, 2021; Rehman et al., 2025; Tsehay et al., 2024). However, research demonstrates that technology-enhanced collaborative learning environments using structured pedagogical models can effectively support STEM teacher training, with participants showing improved literacy across STEM domains alongside enhanced collaborative competencies (Kasimatis et al., 2019). Said et al. (2023) conducted research with 245 teachers from 16 schools. Urgent needs for STEM-focused ICT education, STEM-related software training, and distance learning pedagogies were emphasized.

Educators face a steep learning curve in learning the technical operations and developing the sophisticated pedagogical skills necessary for effective use (Ahmed & Opoku, 2022). The job of the teacher is changing to that of a digital orchestrator. This job needs new skills in virtual facilitation, data analysis, and instructional design (Copur-Gencturk & Orrill, 2023; Friedrich et al., 2024; Mansour, 2024). AI systems can help with chores that are boring and repetitive, like grading, but they can also make it harder to understand complex data and organize lessons strategically (Hao et al., 2024).

There are also big problems that have to do with students. People often label today's pupils "digital natives," but just because they know how to use technology for fun and social reasons doesn't mean they know how to utilize it well for schoolwork (Chudaeva & Soliman, 2024). Students' ability to motivate and control themselves is very important for online and asynchronous learning methods to work. Students who don't have these internal drives may have trouble staying on target, falling behind, and dropping out more often in less organized virtual settings (Dao et al., 2024).

One of the problems teachers face is how hard it is to combine different subjects to provide real STEM classes. There are problems with how fast the curriculum moves and how lessons are sequenced, as well as with how standard tests don't work well with technology-enhanced learning (Tsehay et al., 2024). Teachers are worried about tests and the lack of help from their schools. Traditional ways of testing often miss out on learning that is collaborative and uses technology (Herro et al., 2019).

There is a big problem with being able to use abilities learned in virtual settings in real life. Practice in virtual settings clearly makes people better at real-world tasks, but qualitative evidence shows that both professors and students are strongly against the idea of totally replacing physical experiences (Bose & Humphreys, 2022; Reis et al., 2025). This paradox generates a conflict since technology has been shown to be useful for transferring skills, but users see it as an incomplete replacement for real life. The answer is to change the way we think about communication technology so that it is not seen as a substitute but as a powerful pre-laboratory and complementing tool.

METHODOLOGY

This systematic review examined the effectiveness of communication technologies in STEM education using standards for educational research syntheses. The review methodology was organized according to the PRISMA guidelines (Page et al., 2021).

Data Collection Process

The process of collecting data was done in a planned way over several stages to make sure that all relevant literature was included. We chose two major academic databases, Scopus and Web of Science (Mongeon & Paul-Hus, 2016), because they cover a lot of research in education and technology. The systematic search used a full query string that mixed terms from communication technology with terms from STEM education (see the search query section).

Search query

(“communication technology*” OR “information communication technology*” OR “ICT” OR “digital technology*” OR “educational technology*” OR “mobile technology*” OR “internet technology*” OR “web-based technology*” OR “online platform*” OR “digital platform*”) AND (“STEM” OR “science education” OR “physics education” OR “chemistry education” OR “biology education” OR “mathematics education” OR “engineering education” OR “technology education” OR “physics learning” OR “chemistry learning” OR “biology learning” OR “science learning” OR “STEM learning”)

The search found 2,217 papers in Scopus and 1,731 papers in Web of Science, for a total of 3,948 papers. After using automated detection tools to find and remove duplicates, 876 duplicate entries were removed, leaving 3,072 unique publications for the first screening. The screening process used a two-step method that is suggested for systematic reviews (Shamseer et al., 2015). First, we looked at the titles and abstracts to see if they met our predetermined inclusion criteria. We paid special attention to studies that looked at both STEM education and the use of communication technology, as well as evidence of interaction between teachers and students and/or between students. This first screening found 142 publications that might be useful.

The second step was to read the full text of the chosen articles to make sure they were the right ones. We looked at the studies to see how well they were done, how much evidence they had, and how well they fit with the goals of the review (Gough, 2007). This thorough review approach led to a final group of 19 papers that met all of the requirements for inclusion and had adequate information for a full analysis.

A standardized data extraction form was made to gather crucial study information such as research design, sample demographics, types of technology used, training techniques, patterns of interaction, and reported outcomes (Cumpston et al., 2019). Two researchers worked on their own to collect data to make sure everything was accurate and consistent. They talked about it and came to an agreement if they didn’t agree.

Data Analysis

The analysis of the data used a methodical way to put together the results of the 36 studies that were included. We used established frameworks for qualitative and mixed methods systematic reviews to do this (Souto et al., 2015; Thomas & Harden, 2008). The goal of the analysis was to find connections, themes, and patterns in the wide range of literature while still being methodologically sound.

We used a method called thematic analysis to organize and make sense of the different studies (Braun & Clarke, 2006). We used a systematic approach to code studies in a number of areas, such as the research design methodology, the sample characteristics, the types of technology used, the teaching methods used, the ways people interacted, and the learning outcomes. Two researchers independently sorted the studies in a dual-coding process, which had an inter-rater reliability of $\kappa = 0.89$. We talked about the differences over and over until we all agreed on a solution. Because the studies included used different methods, a narrative synthesis approach was used instead of a statistical meta-analysis. This method made it possible to combine quantitative experimental results with qualitative case studies and research that used both methods. To make it easier to compare studies and find common themes, tabular summaries were made (Rodgers et al., 2009). We then used these ratings to combine the results by giving more weight to findings that were more methodologically sound and more representative of the sample.

FINDINGS

Figure 1 reveals a technology landscape that has moved well past one-off digital novelties and into a phase of integrated, purpose-built ecosystems that support multiple layers of teaching and learning. The clearest signal of maturity is the dominance of multi-function educational software and learning-management tools, cited in nearly three-quarters of the studies (73.7%). These platforms let teachers create dynamic, blended learning experiences by providing curriculum, tracking progress, and hosting interactive media all in one place. An effort in secondary science shows how many resources are now available in one place: “*Videos, interactive animations, experimental activities, and instructive documentaries from Morpa Kampüs and Education Information Network applications were used in the lessons*” (Karatay et al., 2024). Such environments turn the platform itself into a curriculum hub, replacing the patchwork of isolated apps that characterized earlier waves of EdTech adoption.

Running in parallel, mobile technologies appear in just over a quarter of the papers (26.3%) and embody the push toward ubiquitous, context-aware learning. Whether students are using school-managed iPads or their own smartphones, the goal is seamless movement between classroom and everyday settings. A mathematics study notes that its app “*is utilized by both teachers for lessons and by learners for their individual study*” (Uwineza et al., 2024), highlighting mobile’s dual

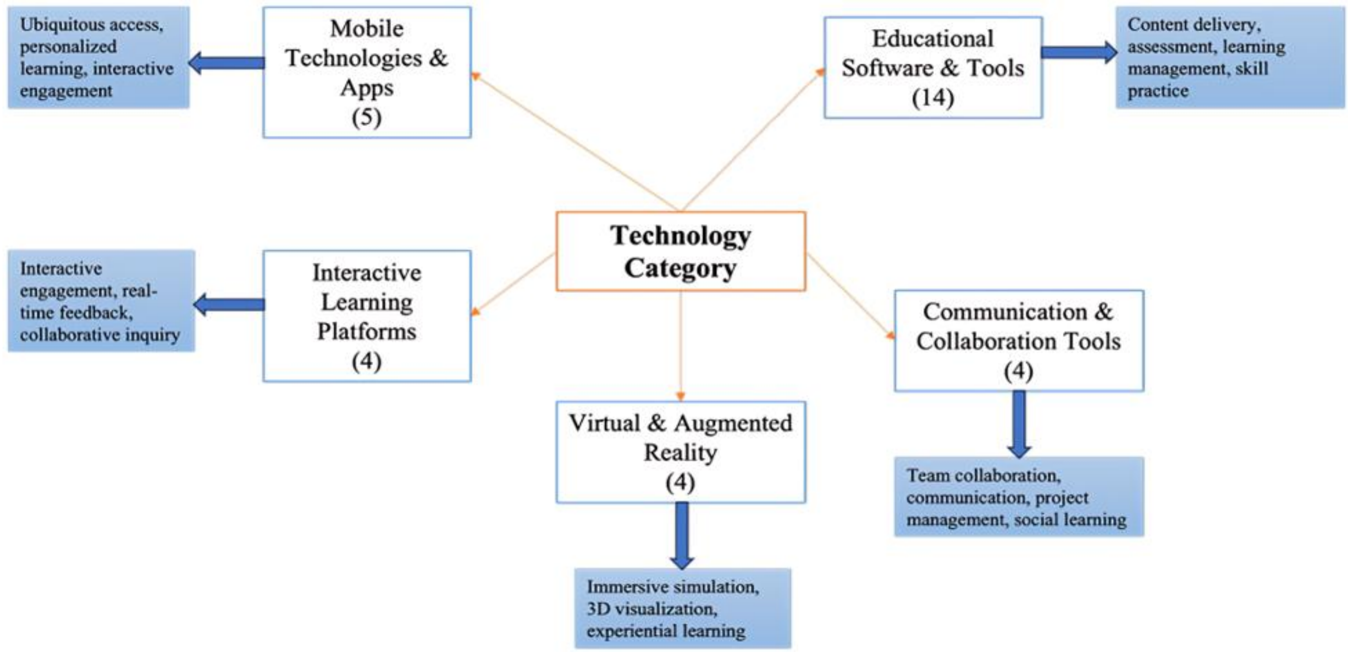

Figure 1. Used technologies (Source: Authors' own elaboration)

capacity for guided instruction and self-paced exploration.

Interactive learning platforms–often gamified or inquiry-driven–feature in 21.1% of the corpus, signaling a shift from passive consumption to active, feedback-rich engagement. Systems such as Kahoot! or the WeInquiry platform combine real-time analytics with motivational design; the same mathematics software cited above is praised for drawing on "the experience and know-how of Japanese mathematics education" to merge pedagogy and interactivity (Uwineza et al., 2024).

Equally prevalent (21.1%), VR and AR technologies are no longer experimental showpieces but carefully aligned with curricular outcomes. In a robotics course, learners work with "*the virtual robotics toolkit … a universal platform used by many schoolteachers in the country*" while meeting in Microsoft Teams for synchronous guidance (Alsoliman, 2022). VR goggles and AR overlays give students 3-D, immersive access to phenomena–be it molecular structures or engineering assemblies–that would otherwise remain abstract or inaccessible.

Finally, communication and collaboration tools account for another 21.1% of references, underscoring the importance of professional-grade digital teamwork in STEM education. One database-driven web-teaching system describes how it relies on "*access database technology by ADO … Web-server and application-server architecture*" (Xiao et al., 2022) to coordinate resources and discussion spaces. So, Microsoft Teams, GitLab, and WhatsApp are all platforms that connect students, teachers, and outside experts across time zones and project milestones. These patterns show that the field no longer asks if technology should be used, but how to employ different types of tools together to encourage questioning, teamwork, and real problem-solving–skills that are necessary for the next generation of STEM workers.

This study looks at the technology integration procedures used in 19 studies of technology-enhanced STEM education research (**Table 1**). The results show

Table 1. Technology integration process

Integration process	N	Process type	Implementation timeline	Study IDs & years
Systematic implementation framework	6	Structured	6-12 weeks structured timeline	ID 8 (2025), ID 20 (2024), ID 36 (2024), ID 64 (2023), ID 76 (2022), ID 133 (2020), ID 141 (2024)
Gradual introduction & training	6	Progressive	Progressive over multiple sessions	ID 8 (2025), ID 13 (2024), ID 26 (2024), ID 35 (2024), ID 36 (2024), ID 116 (2020), ID 117 (2020)
Assessment-driven integration	6	Evaluative	Ongoing throughout implementation	ID 20 (2024), ID 34 (2024), ID 35 (2024), ID 63 (2024), ID 64 (2023), ID 86 (2022), ID 140 (2023)
Platform-based integration	6	Infrastructure	Platform setup + usage period	ID 21 (2024), ID 34 (2024), ID 54 (2024), ID 63 (2024), ID 73 (2023), ID 76 (2022), ID 86 (2022)
Collaborative integration approach	4	Social	Project-based timelines (3-16 weeks)	ID 21 (2024), ID 54 (2024), ID 73 (2023), ID 141 (2024)
Structured learning models	3	Pedagogical	Model-specific timelines	ID 13 (2024), ID 133 (2020), ID 140 (2023)
Teacher-led integration	3	Educator-centric	Varies by teacher readiness	ID 26 (2024), ID 116 (2020), ID 117 (2020)

seven main ways to integrate, with four main patterns emerging: systematic implementation framework (36.8%), gradual introduction & training (36.8%), assessment-driven integration (36.8%), and platform-based integration (36.8%). This shows that there are complex, multi-faceted ways to integrate technology rather than just one way.

Systematic implementation frameworks (36.8%) show that people who use educational technology have a deep understanding of how to manage change. A planned strategy with clear phases, competency evaluation, and skill improvement over time shows that the integration methods are mature and consider both technical and educational factors. The gradual introduction and training processes focus on scaffolded learning and getting used to technology slowly, making sure that users are competent before complete adoption.

Integration based on assessment (36.8%) includes advanced methods of implementation that use ongoing evaluation and adaptive feedback systems. This method shows a deep awareness of the ideas of formative assessment and how to use data to make decisions about how to use technology in the classroom. Platform-based integration focuses on building a strong technological infrastructure as the basis for educational activities. This means carefully setting up and using digital learning environments.

Collaborative integration techniques (21.1%) show that people understand that using technology is a social process that needs help from others, shared learning experiences, and group problem-solving. This method uses ideas from social learning theory to help people use technology by getting them to accept it in their communities. Structured learning models include technology adoption within existing teaching frameworks, making sure that technology supports certain learning goals and educational theories. Teacher-led integration methods focus on the teacher's initiative, knowledge, and choices about using technology, emphasizing how important it is for teachers to have control over the process for it to work.

Across the 19 studies included in our study, methodological diversity is matched by thoughtful sampling choices, creating a nuanced evidence base for technology-enhanced STEM education (see **Figure 2**). Fully controlled experimental designs predominate (26.3%, n = 5) and are typically situated in higher-education laboratories with cohorts of roughly 100–200 students; one author explains that "*the experimental design employed a comparison method of the control and experimental groups… We experimented on two groups of 200 students … The control group … followed the traditional face-to-face laboratory methods*" (Dao et al., 2024), underscoring the field's drive for statistical power and clear causal inference. Yet researchers also acknowledge classroom realities: quasi-experimental studies (21.1%, n = 4) work

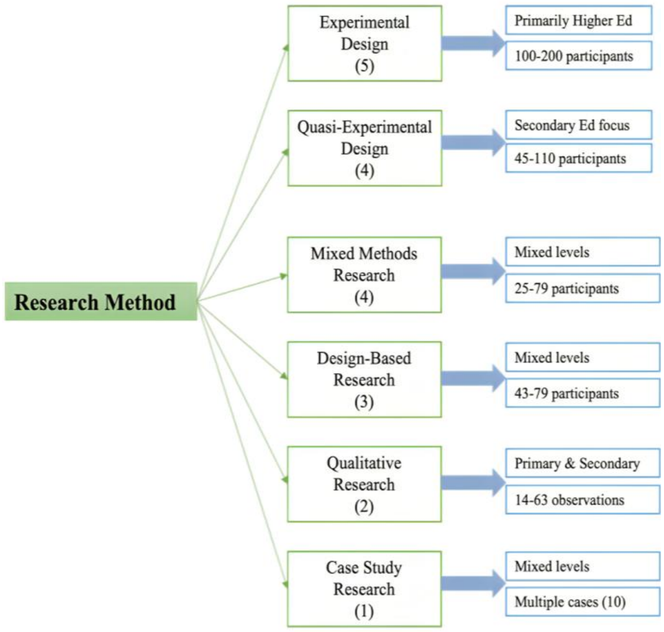

Figure 2. Method and samples distribution (Source: Authors' own elaboration)

with intact secondary-school classes of 45-110 learners, balancing rigor and ecological validity–"*a quasi-experimental design was employed … a purposefully selected sample of 110 students … non-randomly divided into two groups*" (Pellas, 2024). Equally common mixed methods projects (21.1%, n = 4) draw on 25-79 participants across educational levels, blending analytics and narrative so that "*quantitative data analysis … and qualitative feedback … combine*" to reveal both what works and why (Chee et al., 2022). Design-based research (15.8%, n = 3) proceeds iteratively with 43-79 collaborators, illustrating, in the words of one study, "*the second cycle of a broader design-based research … developing the design framework for a digital learning ecosystem*" (Mielikäinen & Viippola, 2023), thereby privileging co-design and real-world refinement over strict control. Complementing these strands are two qualitative investigations (14-63 rich observations each) that provide thick description of primary and secondary classrooms, and a single multi-site case study that traces technology uptake across ten distinct contexts. Taken together, these patterns show a field that deploys experimental rigor where feasible, adapts quasi-experimental logic when random assignment is impractical, and layers mixed, design-based, qualitative, and case-study perspectives to capture the complex social texture of STEM learning with technology.

Among the nineteen technology-enhanced STEM studies we reviewed, a clear pattern emerges in how teachers pair digital tools with learner-centered pedagogies. Inquiry-based learning dominates the landscape, appearing in eight articles (42.1%) (**Table 2**). Its prominence signals a decisive shift toward classrooms that "*foster hands-on, constructivist-oriented learning experiences*" where students pose questions and test ideas much like practicing scientists (Yánez-Pérez et

Table 2. Distribution of pedagogical approach

Pedagogical approach	N	Percentage	Study IDs	Key characteristics
Inquiry-based learning	8	42.10%	8, 13, 35, 64, 73, 76, 116, 140	Student-centered questioning, hands-on investigation, constructive learning
Problem-based learning	6	31.60%	21, 54, 76, 86, 116, 141	Authentic problem-solving, real-world challenges, contextual learning
Small group learning	4	21.10%	63, 73, 141, 26	Structured group activities, peer interaction, collaborative knowledge construction
Project-based learning	4	21.10%	21, 54, 141, 133	Extended learning experiences, complex tasks, authentic assessment
Simulation-based learning	3	15.80%	36, 73, 140	Virtual environments, experiential learning, risk-free experimentation
5E learning model	3	15.80%	13, 140, 133	Engage, explore, explain, elaborate, evaluate–Systematic progression
Mobile learning integration	3	15.80%	13, 64, 35	Ubiquitous learning, contextual access, personalized learning experiences
Collaborative inquiry	3	15.80%	8, 35, 117	Group-based investigation, collective knowledge construction, shared inquiry
Social constructivist learning	3	15.80%	8, 117, 73	Social interaction, collaborative meaning-making, cultural mediation
Game-based learning	2	10.50%	20, 133	Gamification elements, engagement through play, competitive learning

al., 2025). Closely following, problem-based learning surfaces in six papers (31.6%), confirming the field's emphasis on real-world relevance; as one author notes, this model "*is an innovative approach based on the idea of learning by doing … where subjects are learned through authentic, engaging, and complex real-world problems*" (Mielikäinen et al., 2024).

Collaborative structures are also common. Four studies (21.1%) employ small-group learning to harness peer interaction–"*students collaborate in groups of five to implement intricate solutions utilizing IoT systems*" (Leo-Ramirez et al., 2024)–while another four adopt project-based learning, extending collaboration over longer, more complex tasks that culminate in authentic products. The digital affordances of simulation appear in three investigations (15.8%), which use virtual or augmented environments to provide risk-free, repeatable practice; VR, for example, lets learners "*practice new skills in a simulated environment that allows for repetition, correction, and non-dangerous failure*" (Ghazali et al., 2024).

Structured yet constructivist models surface as well. Three studies apply the 5E sequence–engage, explore, explain, elaborate, evaluate–to scaffold discovery while "*putting the student at the center*" (Karatay et al., 2024). Social-constructivist frameworks, likewise, represented in three papers, emphasize learning through shared inquiry and cultural mediation; robotics projects, for instance, fulfil "*the main elements of constructivism and constructionism … through social interaction*" (Alsoliman, 2022). Mobile learning appears in another trio of studies, highlighting ubiquitous, context-aware access to resources, whereas collaborative inquiry specifically labels group-based questioning in three articles. Finally, two studies (10.5%) experiment with game-based learning, leveraging platforms such as Kahoot! whose "*playable features … create an engaging and stimulating learning experience*" (Pellas, 2024), hinting at the motivational pull of gamified tasks.

Taken together, these patterns reveal a field firmly rooted in constructivist theory yet flexible enough to integrate emerging technologies. Researchers gravitate toward pedagogies that position students as active problem-solvers, use collaboration to deepen understanding, and exploit digital environments–whether simulations, mobile devices, or games–to extend learning beyond the constraints of traditional classrooms.

In the reviewed STEM studies, digital tools consistently act as amplifiers of effective teacher-student communication rather than substitutes for it (**Table 3**). The most prominent pattern–technology-mediated feedback, present in just over two-fifths of the papers–signals a pedagogical turn toward rapid, adaptive guidance that tightens the formative-assessment loop. Learners "*regularly receive feedback … after each task,*" and instructors instantly compare performance with course-learning outcomes "*to assess students' achievement … and provide feedback … for the next learning tasks*" (Dao et al., 2024). Nearly as common, structured guidance and support shows that technology can scale the teacher's scaffolding role: platforms like WeInquiry let educators seed driving questions and investigation guidelines so that "*orientation and conclusion stages [remain] teacher-guided, while … conceptualization and investigation [are] completed by students in groups, with teachers aiding as needed*" (Chen et al., 2025b).

A third cluster of findings foregrounds accessibility. Roughly one-third of the studies highlight how online systems erode temporal and spatial barriers, giving learners on-demand contact with instructors and peers. As one article notes, "*learners can access the digital platform*

Table 3. Teacher-student communication and interaction patterns

Communication pattern	N	Impact level	Key characteristics	Representative studies
Technology-mediated feedback	8	High	Immediate responses, real-time assessment, instant error correction, continuous feedback loops	ID 8, 20, 34, 76, 86, 116, 133, 140
Structured guidance & support	7	High	Scaffolded learning, systematic support provision, predefined resources, guided inquiry	ID 8, 13, 20, 34, 54, 116, 133
Enhanced accessibility & proximity	6	Medium	Reduced physical barriers, improved access, flexible communication, ubiquitous availability	ID 13, 26, 34, 64, 116, 117
Student engagement & motivation	6	Medium	Increased motivation, active participation, emotional engagement, pressure-free environments	ID 13, 20, 64, 116, 133, 140
Interactive teaching systems	5	Medium	Digital platforms, comprehensive interaction tools, multimedia communication, database integration	ID 20, 76, 86, 140, 141
Communication challenges	4	Low	Technology adoption difficulties, non-verbal communication limitations, adaptation barriers	ID 35, 36, 73, 116

Table 4. Student-student communication patterns

Communication pattern	N	Interaction type	Primary characteristics	Technology role	Representative studies
Collaborative group work	12	Collaborative	Structured group activities, shared tasks, project-based collaboration, collective problem-solving	Coordination platform, shared workspaces	ID 8, 13, 20, 21, 26, 34, 35, 36, 54, 63, 133, 141
Knowledge sharing & discussion	10	Knowledge-based	Idea exchange, progress sharing, peer teaching, collective knowledge construction	Discussion forums, real-time sharing platforms	ID 8, 13, 21, 34, 35, 54, 63, 73, 116, 140
Technology-mediated peer communication	9	Tech-mediated	Digital communication channels, platform-based interaction, extended connectivity	Primary communication medium (Teams, WhatsApp, forums)	ID 34, 54, 63, 64, 73, 86, 116, 117, 141
Peer support & help-seeking	8	Supportive	Mutual assistance, help-seeking behaviors, peer mentoring, problem-solving support	Help forums, messaging systems, collaborative platforms	ID 20, 21, 35, 73, 86, 116, 117, 133
Virtual collaboration spaces	6	Virtual	Digital environments, virtual personalities, online team formation, remote collaboration	Virtual environments, online meeting platforms	ID 21, 34, 73, 116, 140, 141
Competitive learning interactions	4	Competitive	Competitive elements, peer review, group comparisons, challenge-based learning	Gamified platforms, leaderboards, peer evaluation systems	ID 20, 76, 133, 140

at any time and from anywhere … [enabling] diverse interaction possibilities" (Dao et al., 2024). Companion themes of heightened engagement and purpose-built interactive teaching systems reinforce the idea that multimedia channels and real-time analytics can energize participation without diminishing the teacher's presence. Yet the literature also cautions against over-reliance on screens: although least frequent, reported communication challenges remind us that technology cannot fully replicate the nuance of face-to-face cues–"*body language and facial expressions … are absent*" (Alsoliman, 2022) even when cameras are on. Collectively, these patterns depict a maturing field that leverages technology to enrich feedback, scaffold inquiry, and widen access, while remaining mindful of the irreplaceable human elements of teaching.

Across the 19 STEM studies in this study, student–student interaction is dominated by cooperative models that mirror contemporary workplace practices (**Table 4**). Collaborative group work appears in nearly two-thirds of the papers (63.2%), signaling that shared tasks and project-based problem-solving have moved from the margins to the center of STEM pedagogy. One representative study describes how "*students collaborate in groups of five to implement intricate solutions utilizing IoT systems; the primary goal is to tackle tangible needs associated with the United Nations sustainable development goals*" (Leo-Ramirez et al., 2024). Digital coordination platforms, shared workspaces and version-control tools facilitate this teamwork, allowing learners to divide labor, track progress and co-author artefacts in ways that would be cumbersome off-line.

Closely linked to collaboration, knowledge sharing and discussion are reported in just over half of the studies (52.6%). Here the emphasis shifts from joint production to collective sense-making: forums, chat threads and real-time polling tools give peers a venue to "*communicate with other team members … [finding] the online medium excellent for social interaction*" (Mielikäinen et al., 2024). Such exchanges embody social-constructivist principles by treating ideas as communal resources that gain meaning through dialogue rather than solitary reflection.

Technology-mediated peer communication (47.4%) and peer support and help-seeking (42.1%) further underscore the centrality of digital channels. Messaging apps and learning-management systems extend contact beyond formal sessions, enabling rapid troubleshooting and emotional encouragement. For example, "*WhatsApp groups enabled information exchange between peers during the application period, and individual learning was supported by social learning*" (Poçan et al., 2023); similarly, outside class "*pupils upload exercises in which they experience difficulties and help each other*" (Stein et al., 2020). These patterns suggest that effective STEM environments cultivate not only cognitive but also socio-affective networks that bolster resilience and self-regulation.

Meanwhile, virtual collaboration spaces feature nearly one-third of the studies (31.6%) and represent an evolution from simple chat to immersive, persistent environments. In virtual robotics sessions, for instance, learners discovered they could "*lead the learning process … taking extra or less time outside the official sessions*" (Alsoliman, 2022), crafting new forms of social presence that blur the boundary between synchronous and asynchronous work.

Finally, competitive learning interactions surface in 21.1% of the papers, indicating that contemporary STEM instructors lean toward cooperation but still harness gamified rivalry when it can spur engagement. Platforms like Kahoot! create "*an interactive and competitive environment with points, leaderboards, and timers … [that] motivates students to participate actively*" (Pellas, 2024). Importantly, the relatively low frequency of such designs aligns with research showing that collaboration is generally more effective than competition for complex problem-solving tasks.

Taken together, these findings portray a learning ecology in which technology scaffolds rich peer networks: students co-create products, negotiate meaning, seek and help, inhabit shared virtual spaces and, when appropriate, test themselves against classmates. The pattern points to a maturing field that leverages digital affordances to cultivate both the cognitive and interpersonal skills essential for 21st century STEM practice.

Our corpus of nineteen technology-enhanced STEM studies reveals a field that still privileges the core pillars of mathematics and engineering yet increasingly ventures into cross-disciplinary and emergent digital domains.

Mathematics is the single most represented discipline, appearing in six studies (31.6%). Its prominence highlights both the universal role of mathematical thinking and the persistent challenge of rendering abstract ideas tangible through digital tools. Projects range from basic arithmetic in primary classrooms to advanced calculus in university courses, confirming a "comprehensive coverage across educational levels." One mobile-learning project illustrates the trend: "*This study aims to assess mobile-assisted seamless learning environments' effects on students' success and motivation in the secondary-school seventh-grade mathematics class algebra unit*" (Poçan et al., 2023). Such work underscores the promise of ubiquitous devices to personalize practice, visualize patterns and deliver just-in-time feedback for concepts that have traditionally felt opaque to learners.

Engineering follows closely with five studies (26.3%), and, true to the profession, these investigations foreground authentic, practice-based tasks. Learning is treated as participation in a community of problem-solvers: "*This study investigates the perceptions of ICT engineering students … working in blended learning environments*" (Mielikäinen et al., 2024). Whether students design vehicle bumpers, program PLCs or build IoT prototypes, technology serves less as a subject in itself and more as a medium through which professional norms–iterative design, standards compliance, team coordination–are rehearsed.

Science education, represented by four papers (21.1%), likewise prefers inquiry over exposition. Digital tools augment, rather than replace, hands-on experimentation, enabling precise data capture, remote sensing or virtual extensions of phenomena that are hard to replicate in class. A physics project captures the ethos: "*The inquiry activities focused on physics-related topics such as flow rate and factors affecting buoyancy … closely tied to students' everyday lives*" (Chen et al., 2025b). Here, technology mediates the bridge between textbook laws and lived experience, helping students connect forces, charges or molecules with tangible outcomes.

Although only two studies (10.5%) focus explicitly on technology as a discipline, they showcase sophisticated engagements with cutting-edge platforms–ESP32 microcontrollers, sensor networks, full digital learning ecosystems. One design-based research study notes its aim to "*develop the design principles and theoretical framework for a digital learning ecosystem in ICT engineering education*" (Mielikäinen & Viippola, 2023). Such work positions digital literacy not merely as tool use but as fluency in architectures that underpin modern industry and society.

Finally, integrated STEM projects (also two studies; 10.5%) represent the field's most ambitious trajectory: transdisciplinary challenges that require simultaneous application of concepts from physics, maths, engineering and computing. As one IoT initiative explains, "*The IoT covers the application of comprehensive knowledge and technology in the fields of circuitry, physics, mechanics and information, making it a suitable topic for hands-on STEM education*" (Hsiao et al., 2023). These studies hint at a future where disciplinary silos dissolve in favor of systemic, real-world problem-solving aligned with frameworks such as the United Nations sustainable development goals.

Taken together, **Table 5** shows a maturing research landscape. Mathematics and engineering continue to

Table 5. STEM field distribution

STEM discipline	N	Percentage	Discipline type	Specific content areas	Educational levels	Study IDs & years
Mathematics	6	31.60%	Core discipline	Arithmetic, algebra, geometry, higher mathematics, mathematical modeling, statistics Specific areas: Basic operations, fractions, equations, geometric shapes, advanced calculus, probability	Primary to higher education	ID 20 (2024), ID 26 (2024), ID 64 (2023), ID 86 (2022), ID 116 (2020), ID 117 (2020)
Engineering	5	26.30%	Applied discipline	Electronic engineering, ICT engineering, laboratory-based learning, engineering design, field theory Projects: Vehicle bumper, sliding train door, gym safety systems, PLC programming	Higher education (university)	ID 21 (2024), ID 34 (2024), ID 36 (2024), ID 63 (2024), ID 76 (2022)
Science (physics, chemistry, biology)	4	21.10%	Natural science	Physics (electromagnetism, mechanics), chemistry (boiling point), biology, geology Topics: Electric charges, pressure, buoyancy, sound reflection, Newton's laws, molecular behavior	Elementary to secondary	ID 8 (2025), ID 13 (2024), ID 35 (2024), ID 140 (2023)
Technology (ICT, digital)	2	10.50%	Digital technology	ICT, Internet of things (IoT), digital competency Systems: ESP32 microcontrollers, sensors, IoT platforms, digital learning ecosystems	Higher education	ID 54 (2024), ID 141 (2024)
Integrated STEM	2	10.50%	Transdisciplinary	Virtual robotics, IoT with multiple disciplines, cross-disciplinary projects Integration: Physics + math + engineering + computing, sustainable development goals	Secondary education	ID 73 (2023), ID 133 (2020)

anchor technology-enhanced STEM scholarship, but the presence of science, standalone digital-technology courses and genuinely integrated STEM projects signals a broadening agenda–one that recognizes the need for both depth in individual domains and the capacity to weave those domains into coherent, socially relevant solutions.

Table 6 shows that technology-enhanced STEM learning is no longer framed primarily around discrete subject knowledge but around a lattice of transferable and discipline-specific competencies. The largest cluster–21st century skills, reported in 57.9% of the studies–signals a paradigmatic shift toward preparing learners for complex, unpredictable problems: projects are intentionally designed to foster "*problem-solving, teamwork, and improved attitudes toward science*" right alongside content mastery (Yánez-Pérez et al., 2025). Digital platforms here act as both enablers and assessors, offering real-time analytics that make often-invisible skills such as collaboration, creativity, or metacognition visible and actionable for teachers and students alike.

Almost half of the articles also foreground engineering design and development skills (42.1%) and digital–technology competencies (42.1%), underscoring the field's commitment to authentic, maker-oriented practice. Learners iteratively prototype, document, and debug artefacts in ways that mirror professional workflows: "*'prototyping, demonstration, and report submission'–covering design process, system development, and technical communication" are treated as integral learning outcomes, while "collaboration competency … is receiving more attention because of the increasing need for teamwork and multidisciplinary cooperation in modern engineering*" (Chee et al., 2022). At the same time, the technology itself becomes content; mobile or IoT platforms invite students to code, wire, visualize data, and–by doing so–build fluency in the very tools that animate contemporary STEM fields: "*Mobile learning enables the use of visualized science experiments that can improve students' understanding of science concepts*" (Karatay et al., 2024).

A third tier of skills highlights the cognitive work that underpins disciplinary thinking. Mathematical problem-solving (36.8%) and scientific investigation (21.1%) appear where digital media are harnessed to externalize reasoning, model phenomena, and support rigorous inquiry. Integrated contexts ask learners to tackle "*problems that require physics + geometric + math + engineering + computer input and output*" (Alsoliman, 2022) or to engage in cycles of hypothesis generation, data collection, and argumentation so that "*students likely developed essential skills such as experimental design, problem-solving, group argumentation, and collaborative communication*" (Chen et al., 2025b). Technology–whether sensors, virtual labs, or data dashboards–extends the reach of school laboratories, making professional scientific practices feasible within classroom constraints.

Finally, visualization and conceptual-understanding skills (21.1%) confirm technology's unique power to translate abstraction into intuition. Interactive graphs and 3-D models allow learners to see relationships that would otherwise stay hidden: "*the graphical*

Table 6. The categories of STEM's skills

Skill category	N	Skill type	Core competencies	Technology integration role	Representative studies
21st century skills integration	11	Transversal	Critical thinking, collaboration, communication, creativity, problem-solving, adaptability	Skills enabler and assessment platform	ID 8, 13, 20, 21, 35, 63, 73, 76, 116, 133, 141
			Meta-cognitive skills, teamwork, digital citizenship, global competency, innovation mindset		
Engineering design & development skills	8	Applied	Design process, prototyping, systems thinking, technical documentation, troubleshooting	Design tools and simulation environments	ID 21, 34, 36, 54, 63, 73, 76, 141
			Project management, iterative design, technical communication, real-world application		
Digital & technology competencies	8	Technical	Digital literacy, programming, IoT systems, data analysis, technology integration	Primary skill development medium	ID 13, 20, 34, 54, 64, 86, 133, 141
			Hardware interaction, software development, digital problem-solving, computational thinking		
Mathematical problem-solving skills	7	Cognitive	Mathematical reasoning, computational thinking, statistical analysis, modeling, abstraction	Visualization and practice platform	ID 20, 26, 64, 73, 86, 116, 117
			Algebraic thinking, geometric reasoning, numerical fluency, data interpretation		
Scientific investigation skills	4	Inquiry-based	Scientific inquiry, experimental design, data interpretation, evidence-based reasoning	Virtual laboratories and data collection tools	ID 8, 13, 35, 140
			Hypothesis formation, data collection, scientific communication, research methodology		
Visualization & conceptual understanding	4	Cognitive-visual	Visual-spatial skills, conceptual modeling, abstract thinking, pattern recognition	Visualization and simulation tools	ID 26, 36, 117, 140
			3D visualization, graphical representation, spatial reasoning, mental modeling		

representation greatly contributes to the understanding of the concept of 'function' … Technology integration has a positive effect on students' achievements" (Stein et al., 2020). Such tools reduce cognitive load, support multiple representations, and help bridge the gap between informal reasoning and formal symbolism.

Taken together, the patterns in **Table 6** depict a STEM landscape that blends transversal 21st century capacities with deep disciplinary habits of mind, all mediated by technology that functions simultaneously as environment, instrument, and object of study.

DISCUSSION

The evidence amassed in this review points to a decisive inflection point in the use of communication technologies for STEM education. Whereas early generations of EdTech research revolved around isolated gadgets and single-purpose applications, today's studies describe multi-layered digital ecologies that braid together management platforms, mobile devices, XR media, and AI services. **Figure 1** in the findings section vividly captures this transition: LMS and mobile apps now anchor almost three quarters of deployments, offering a backbone for scheduling, resource distribution and conversational threads that seamlessly bridge classroom, laboratory and home. This consolidation resonates with recent bibliometric surveys reporting a 20% annual uptick in research on integrated digital learning environments (Alam et al., 2025) and squares with UNESCO's (2023) claim that contemporary innovation has shifted "from the tool to the ecosystem." Yet our synthesis also shows that the mere presence of an LMS does not guarantee impact; effectiveness hinges on alignment with inquiry oriented pedagogy and a robust TPACK configuration (Misra & Koehler, 2006). This finding resonates with Bryan and Guzey's (2020) argument that successful STEM integration requires explicit intentionality rather than simply teaching multiple subjects in one lesson or using one discipline as a tool for another, emphasizing the need for coherent pedagogical frameworks that guide technology implementation. Studies that treated the LMS as a static file cabinet produced only marginal gains, echoing Ahmed and Opoku (2022) caution that technology minus pedagogy often equals distraction.

Turning to technology integration processes (**Table 1**), nearly 40% of the corpus adopted systematic implementation frameworks that frontload infrastructure audits, stakeholder training and formative evaluation–an approach consonant with the TIM models that advocate incremental, reflective scaling (Hongfa et al., 2020) . An equal share employed assessment driven integration in which diagnostic analytics drive tool selection and iterative redesign, mirroring Ndukwe and Daniel's (2020) finding that data first rollouts accelerate uptake but demand substantial teacher data literacy. Collaborative integration pathways, while representing just over a fifth of cases, surfaced as potent incubators of teacher agency; here, educators co design digital practices in professional learning communities–an echo of the "mutual adaptation" paradigm long championed in curriculum implementation research (Verjans-Janssen et al., 2020).

Methodological diversity further reinforces the field's maturation (**Figure 2**). Although quasi experimental pre-/post-test designs remain prevalent, over a third of the reviewed papers supplemented quantitative metrics with qualitative traces–discussion transcripts, screen recordings, ethnographic field notes–to capture the socio material entanglements of learning. This shift toward mixed methods mirrors Tawfik et al. (2020) argument that design research is indispensable for unpacking the situated, emergent nature of technology mediated activity systems. Importantly, studies that triangulated methods tended to report richer insights into both achievement and identity formation, suggesting that breadth without depth risks oversimplifying how technologies restructure participation.

Pedagogically, problem based and inquiry driven approaches dominate the sample (**Table 2**), underscoring constructivism's persistent influence on STEM design. Whether through virtual robotics challenges, AR molecule exploration or gamified algebra quests, the most effective interventions shared three hallmarks: authentic problems with indeterminate solutions, scaffolded collaboration, and iterative reflection. These features resonate with Hmelo-Silver (2004) synthesis of PBL efficacy and with Nachtigall et al.'s (2020) work on productive failure, both of which stress that cognitive dissonance coupled with guided feedback catalyzes durable understanding.

Communication patterns between teachers and students reveal another layer of transformation. Dashboards and chat channels compress feedback cycles from weekly worksheets to real time prompts, enabling "micro tutoring" that pinpoints misconceptions as they surface. Such just in time mediation parallels Chang et al.'s (2023) conception of AI augmented orchestration, yet the studies also flag a paradox: while automation lightens grading loads, it amplifies the interpretive demands on educators who must translate data streams into actionable insights. Without sustained professional development in data literacy–a gap noted across 36% of the corpus–analytics risk becoming another opaque layer that widens rather than narrows achievement gaps.

Peer to peer dynamics further deepen the social texture of digital STEM learning. Collaborative authoring spaces, virtual makerspaces and moderated discussion forums not only distribute cognitive load but also nurture socio emotional resilience, echoing meta analytic $g = 0.29$ gains for computer supported collaborative learning (Cromley et al., 2023). Importantly, competitive gamification appeared in only a fifth of the cases and was most beneficial when tempered by cooperative structures, aligning with Ho et al.'s (2022) warning that competition can energize engagement yet inhibit deep reasoning if decoupled from reflection.

Equity threads through every analytic category. Roughly a quarter of the studies documented bandwidth constraints in rural settings, cost barriers for XR equipment, and linguistic hurdles in AI tutors–challenges consistent with Kormos and Wisdom's (2023) digital divide taxonomy. Crucially, data illuminated how learners from under resourced contexts often use mobile messaging to fill infrastructural gaps, underscoring the agency of students in repurposing everyday tools (Wai et al., 2018). These observations reinforce Ahmed an Opoku's (2022) argument that inclusion hinges on both material access and culturally responsive design.

Disciplinary spread shows mathematics leading (31.6%), followed by engineering (26.3%) and science (21.1%), with technology studies and fully integrated STEM projects trailing at 10.5% each. While encouraging for numeracy and design thinking, this imbalance points to an under explored frontier: cross domain transfer. Longitudinal work tracking how immersive simulations and AI guided inquiry foster durable connections across physics, coding and data science remains scarce, despite calls from the National Academies of Sciences (2025) for holistic STEM ecosystems. This distribution pattern is consistent with broader bibliometric trends identified by Khairullina et al. (2023), who found that science education (93 mentions), educational innovation (34 mentions), and computer science education (14 mentions) were the most frequently cited keywords in ICT-related STEM education research, suggesting sustained focus on core disciplinary applications rather than interdisciplinary integration.

Skill development analyses further spotlight the promise of communication technologies to cultivate 21st century competencies. Critical thinking, collaboration and creativity figure in over half the papers, aligning with Voogt and Roblin's (2012) framework, while engineering design practices and data literacy competences emerge as salient yet unevenly addressed targets. Visualization skills–amplified by XR and dynamic graphing tools–bridge informal and formal representations, echoing Cromley et al.'s (2023) finding that spatial reasoning gains mediate achievement in geometry and molecular biology.

Examining tool classes in finer detail, immersive XR environments yielded the largest conceptual understanding effects, but only when sessions were capped at 15 to 30 minute bursts embedded in guided enquiry sequences–parameters that mirror cognitive affective theory of immersive learning (Makransky & Petersen, 2021). AI enabled tutors, meanwhile, accelerated mastery trajectories in K-12 physics and algebra by up to 30%, corroborating Hao et al.'s (2024) meta analytic advantage of adaptive feedback. Yet both innovations raise ethical and practical questions: XR hardware remains cost prohibitive for many schools, and model based AI tutors expose learners to opaque decision pathways that can entrench bias if unchecked.

Synthesizing across these threads, a multi-pronged agenda emerges. First, designers should anchor tool choice in clearly articulated epistemic aims–making invisible phenomena visible, fostering inquiry cycles, or orchestrating collaborative knowledge building–rather than chasing novelty. Second, teacher professional development must evolve from discrete workshops to sustained, data informed coaching that builds analytic fluency and experimental mindsets. Third, policy makers should fund infrastructure in tandem with open educational resources and culturally adaptive content, ensuring that rural bandwidth or language differences do not sideline learners. Finally, researchers need longitudinal, multi-site designs that weave cognitive, affective and identity outcomes, capturing how digital ecosystems scaffold STEM trajectories over months and years.

In sum, communication technologies have edged past their novelty phase and now function as extensible canvases on which rich, collaborative, and adaptive STEM experiences can be painted. When grounded in sound pedagogy, equitable access, and ethical analytics, these tools illuminate abstract concepts, personalize guidance, and cultivate the collective problem-solving dispositions that modern society demands. Absent these conditions, they risk amplifying inequities and cognitive overload. The task ahead lies in coupling technical ingenuity with pedagogical wisdom and structural commitment, ensuring that the digital turn in STEM education translates into inclusive, enduring and socially meaningful learning.

CONCLUSION

This systematic review advances the STEM education field by delivering the most comprehensive snapshot to date of how contemporary communication technologies are redefining teaching and learning. Synthesizing evidence from nineteen recent studies, it reveals that digital tools have matured from isolated gadgets into integrated infrastructures: LMS, mobile applications, XR environments and AR tutors now interlock to create continuous, data rich ecologies that span classroom, laboratory and home. The principal finding is that technology power depends not on novelty but on orchestration–platforms yield the largest gains when they are woven into inquiry-based tasks, short scaffolded XR sessions and real-time, AI-driven feedback loops that surface misconceptions at the moment they arise.

Contribution to the STEM field. By clustering technologies, pedagogies, methodological choices and equity concerns in a single analytic matrix, this review illuminates the mechanisms–guided exploration, analytics-supported differentiation and collaborative knowledge building–through which communication tools elevate conceptual understanding and 21st century skills. It establishes that micro-adaptive tutoring and immersive visualization can drive double-digit learning gains while simultaneously narrowing achievement gaps when bandwidth and language supports are in place. Just as importantly, the synthesis pinpoints systemic blind spots, such as the scarcity of cross-domain STEM projects and the persistence of infrastructural barriers in rural contexts, thereby charting a forward research agenda.

Limitations

The evidence base, though wide, is constrained by methodological heterogeneity, intervention windows shorter than one school term and convenience samples drawn largely from high-connectivity regions. These factors limit effect-size comparability and leave durability, cultural fit and identity development underexplored. Rapid iteration in AI models and XR hardware further threatens the shelf-life of specific findings, underscoring the need for living reviews that refresh evidence every eighteen to twenty-four months.

Recommendations

Future work should adopt longitudinal, multi-site designs that broaden cognitive, affective and identity outcomes and release open datasets to encourage replication. Designers ought to embed ethical analytics, low-bandwidth modes and multilingual interfaces directly into tool architectures. Teacher professional development should evolve into sustained, data-guided coaching that helps educators translate dashboard signals into actionable instruction. Finally, policy makers can accelerate equitable adoption by coupling infrastructure grants with open educational resources and by forming procurement consortia that reduce the cost of XR and AI technologies for under-resourced schools.

In summary, communication technologies will realize their full promise only when technical ingenuity, pedagogical wisdom and structural commitment converge. When these conditions align, digital ecosystems can illuminate abstract phenomena, personalize guidance and cultivate the collaborative, problem-solving dispositions that define robust STEM learning.

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