

Digital Technology Integration for Quality and Sustainable Science Education: A Systematic Review of Teacher Competence, Pedagogical Design, and Student Learning Outcomes

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Abstract: Digital technology integration has become increasingly important in science education, particularly in efforts to support quality and sustainable learning environment. This systematic review examines how digital technologies are integrated into science education and identifies the roles of teacher competence, pedagogical design, learning outcomes, and contextual conditions. A systematic search of the Scopus database using PRISMA informed procedures identified 136 records; of which 38 studies were included after screening and eligibility assessment. The findings were synthesized into four themes: teacher competence, pedagogical design, learning outcomes, and implementation conditions. The synthesis indicated that digital technologies can support science learning by enhancing visualization, inquiry, engagement, and collaboration when aligned with appropriate pedagogical strategies and supported by adequate implementation conditions. However, technology integration does not automatically produce improved learning outcomes, as its effectiveness depends on teacher readiness, instructional design, infrastructure, and equity of access. The review concludes that digital technology functions as an enabling condition for sustainable science education rather than an independent determinant of learning outcomes.

Keywords: Digital technology integration; Pedagogical design; PRISMA; Quality and sustainable learning environment; Science education

Introduction

Science education contexts are increasingly expected to prepare learners for a world in which scientific understanding, digital literacy, and problem-solving competence are inseparable. Science classrooms are no longer limited to textbooks, teacher explanations, and physical laboratory activities. They increasingly incorporate information and communication technologies, simulations, virtual and remote laboratories, augmented reality, digital notebooks, interactive e-books, social media, computer-supported collaborative learning, sensor-based platforms, and

artificial intelligence tools. These technologies have the potential to make abstract scientific concepts visible, support inquiry and experimentation, expand access to learning resources, and create new forms of interaction between teachers, students, data, and scientific phenomena (Wider et al., 2025).

However, the educational value of digital technology in secondary science learning cannot be assumed from the presence of devices or software alone. The studies synthesized in this review repeatedly indicate that digital integration is shaped by the knowledge, beliefs, self-efficacy, and design capacity of science teachers. Abualrob & Al-Saadi (2025) show that

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ICT teaching self-efficacy, enjoyment, control appraisal, value appraisal, and TPACK significantly predict science teachers' valuation of ICT-enhanced instruction. Similarly, Mansour et al. (2024) demonstrate that TPACK development among secondary STEM teachers depends on the interaction of technological, pedagogical, and content knowledge components, with technological content knowledge playing a particularly important role. These findings show that technology integration is not a purely technical process, but a professional and pedagogical one.

Teacher competence also interacts with classroom design. Technology can be used as a substitute for traditional presentation, but it can also support inquiry, modelling, visualization, argumentation, collaboration, and formative assessment. Hsu et al. (2023) show how a secondary biology teacher's augmented reality integration developed through pedagogical reasoning, reflection, and redesign. López et al. (2025) report that pre-service science teachers' use of content-specific technologies was associated with higher cognitive demand and scientific research skills, whereas Rodríguez & Arévalo (2025) found that teachers may select relevant tools but still design low-cognitive-demand activities. These tensions indicate that the crucial question is not simply whether technology is used, but how it is pedagogically orchestrated.

The outcome evidence is promising but uneven. ICT integration has been associated with improved achievement and motivation in life and earth sciences (Janous et al., 2022), ICT-assisted experiments show a moderate overall effect on K-12 physics learning (Walker & Nouri, 2025; Jiang et al., 2026), and virtual reality laboratories can improve life sciences understanding and science process skills among grade 10 learners in rural schools (Ngema & Motlhabane, 2025). Computer-supported collaborative learning with question-asking scripts can enhance conceptual understanding and critical thinking (Ramirez, 2021), while augmented reality and simulations can improve engagement and attitudes when design conditions are appropriate (Almasri, 2022; Baran et al., 2020). Nevertheless, some technologies increase interest without necessarily producing strong evidence of deeper conceptual change, and some benefits depend on teacher mediation, task quality, and student access.

Implementation conditions are equally important. Technology integration in secondary science education is constrained by infrastructure, internet connectivity, teacher training, curriculum pressure, school leadership, assessment demands, socioeconomic inequality, rural context, and ethical concerns related to artificial intelligence and misinformation. Qashani & Boateng (2026) show that rural physical sciences classrooms face limited ICT use because of weak infrastructure,

insufficient training, and unstable connectivity. Yavuzalp & Öztürk (2026) describe primary, secondary, and third-order barriers to e-argumentation software, including software usability challenges, teacher anxiety, and difficulties related to pedagogical implementation of e-argumentation tools. These findings suggest that technology integration is an ecological process involving teachers, students, schools, and policy systems.

This review therefore addresses an important gap in the literature by providing an integrated synthesis of how digital technology integration operates across science education contexts through the interaction of teacher competence, pedagogical design, learning outcomes, and implementation conditions. Although previous studies have provided valuable insights into specific digital tools, individual learning outcomes, or particular dimensions of teacher competence, these fragmented perspectives provide limited understanding of how technological, pedagogical, human, and contextual factors interact to shape meaningful technology integration.

The novelty of this review lies in its attempt to move beyond technology-centered evaluations by examining digital integration as a multidimensional educational process. Rather than asking whether a particular technology improves learning, this review investigates under what conditions digital technologies become pedagogically meaningful, considering teacher readiness, instructional design, learner outcomes, infrastructure, and equity conditions. This perspective is important because sustainable digital transformation in science education requires more than access to technological resources; it requires alignment among technological affordances, pedagogical goals, teacher capacity, and contextual realities. Therefore, a systematic synthesis is needed to explain why similar digital technologies may produce different educational outcomes across contexts and to identify the enabling conditions required for quality and sustainable science education.

The review is guided by five questions: How are digital technologies integrated across science education contexts?; How do teacher competence, TPACK, self-efficacy, and professional development influence technology integration in science classrooms?; How are digital tools pedagogically designed and implemented to support science learning?; What student learning outcomes are associated with digital technology integration in secondary science education?; and What barriers and enabling conditions shape effective implementation? The scientific contribution of the review is an integrated framework that conceptualizes digital technology integration as a teacher-mediated, pedagogically designed, contextually conditioned process that can support student learning only when

technology, pedagogy, science content, and classroom realities are aligned.

Method

Search Strategy

This review followed a PRISMA-informed systematic literature review design. The main information source was Scopus, using a Boolean search strategy focused on digital technology integration, secondary science learning, and pedagogical implementation. The search string reported in the supplied draft was: ("technology integration" OR "digital technology integration" OR "ICT integration" OR "educational technology" OR "technology-enhanced learning" OR "digital learning" OR "augmented reality" OR "virtual reality" OR simulation OR "virtual laboratory" OR "artificial intelligence" OR ChatGPT OR "computer-supported collaborative learning"); AND ("secondary science" OR "secondary school science" OR "high school science" OR "science education") AND (learning OR teaching OR instruction OR pedagogy OR classroom*). This strategy was designed to capture studies in which digital technology integration was connected to science learning, teaching, instruction, pedagogy, or classroom practice. The search strategy was structured around four conceptual domains: digital technology, science education, learning processes, and implementation conditions.

The broader search framework was structured around four concept blocks. The first block represented digital technology integration, including digital technology, ICT integration, educational technology, technology-enhanced learning, digital learning, augmented reality, virtual laboratories, simulations, artificial intelligence, e-learning, and computer-supported collaborative learning. The second block represented science education, including science learning, science teaching, physics education, chemistry education, biology education, life sciences, and physical sciences. The third block represented secondary education, including secondary school, high school, middle school, junior high school, senior high school, and K-12. The fourth block represented teacher and learning dimensions, including teacher competence, TPACK, self-efficacy, pedagogical design, student engagement, learning outcomes, conceptual understanding, scientific literacy, and science process skills.

The search log supplied in the draft reported that 136 records were identified from Scopus. Records older than 2016 were excluded before screening, leaving 99 records for screening. Document-type and language limits retained English-language journal articles, and scope screening was then used to identify studies

directly relevant to the review focus. The review included 38 studies in the final synthesis.

Eligibility Criteria

Inclusion criteria were defined to ensure that the evidence base corresponded to the title and review questions. Studies were included when they were peer-reviewed journal articles; focused directly on digital technology integration in science education; involved formal science education contexts, including school-level science learning and teacher education settings relevant to science teaching and learning; addressed teacher competence, TPACK, pedagogical design, implementation, learning outcomes, or barriers and enablers; and provided sufficient bibliographic and methodological information for extraction. Studies involving pre-service science teachers were retained when they directly addressed preparation for secondary science teaching, technology-integrated science pedagogy, TPACK, or classroom-oriented lesson design.

Studies were excluded when they were outside science education, focused only on general digital literacy without connection to science learning, addressed higher education without relevance to secondary teacher preparation, or were not peer-reviewed journal articles. Editorials, opinion pieces, theses, book reviews, conference abstracts, non-scholarly commentaries, inaccessible or incomplete records, and duplicate records were excluded. Records were also excluded when they did not address digital technology integration as a substantive component of teaching, learning, assessment, scientific inquiry, or classroom implementation.

Screening, Selection, and Risk-of-Bias Analysis

Screening followed sequential PRISMA logic. The search log indicated that 136 records were identified from Scopus, with no duplicates removed. Thirty-seven records were excluded because they were older than 2016, leaving 99 records for screening. After applying document-type and language limits, 72 English-language journal articles were retained for eligibility assessment. Thirty-four reports were excluded as out of scope, resulting in 38 studies included in the final synthesis. Figure 1 presents the PRISMA-based study selection process, including identification, screening, eligibility assessment, and inclusion stages.

Because the final evidence base includes quantitative, qualitative, mixed-methods, review, bibliometric, and intervention studies, appraisal was treated as a design-sensitive interpretive process rather than a single uniform score. Quantitative and quasi-experimental studies were interpreted with attention to comparison groups, sample size, measurement, statistical reporting, and outcome relevance. Qualitative

studies were interpreted with attention to transparency of sampling, credibility of data collection, thematic analysis, and contextual richness. Mixed-methods studies were interpreted in terms of integration between quantitative and qualitative components. Review and bibliometric studies were interpreted according to database coverage, screening transparency, and methodological alignment with their review purposes. Methodological quality considerations were examined through narrative appraisal according to study design, methodological transparency, and relevance to the review objectives in this manuscript because full-text appraisal records were not supplied; therefore, quality considerations are integrated narratively into the synthesis.

Theoretical Background

Teacher Knowledge Frameworks for Digital Science Teaching

The central theoretical lens for this review is Technological Pedagogical Content Knowledge. TPACK explains why effective technology integration in science teaching requires more than technical skill. Teachers must understand science content, pedagogical strategies, and the affordances and constraints of digital tools, and they must be able to combine these forms of knowledge in specific instructional contexts. Evidence from the reviewed studies supports this view. Chieng & Tan (2021) found that Malaysian secondary science teachers' technology-related knowledge was lower than their non-technology pedagogical and content knowledge, suggesting that teacher preparation must address technology-specific knowledge gaps. Mansour et al. (2024) found that TPACK among secondary science and mathematics teachers in Qatar was shaped by interactions among knowledge components, with technological content knowledge emerging as especially influential.

TPACK is also related to self-efficacy and teachers' affective appraisal of technology (Dewi et al., 2021; Mölgen et al., 2024). Abualrob & Al-Saadi (2025) show that ICT teaching self-efficacy, enjoyment, control appraisal, value appraisal, and TPCK predict teachers' perceptions of ICT value in science education. Jita & Sintema (2022), using the Technology Acceptance Model as a lens, found that pre-service teachers often underestimate their competence to teach science with ICT and that technological knowledge may lag behind technological pedagogical knowledge. Jere & Tsoka (2024) draw on social cognitive theory to show that rural science teachers' self-efficacy in simulation integration is shaped by mastery experience, vicarious experience, verbal persuasion, affective state, teaching experience, and school socioeconomic conditions.

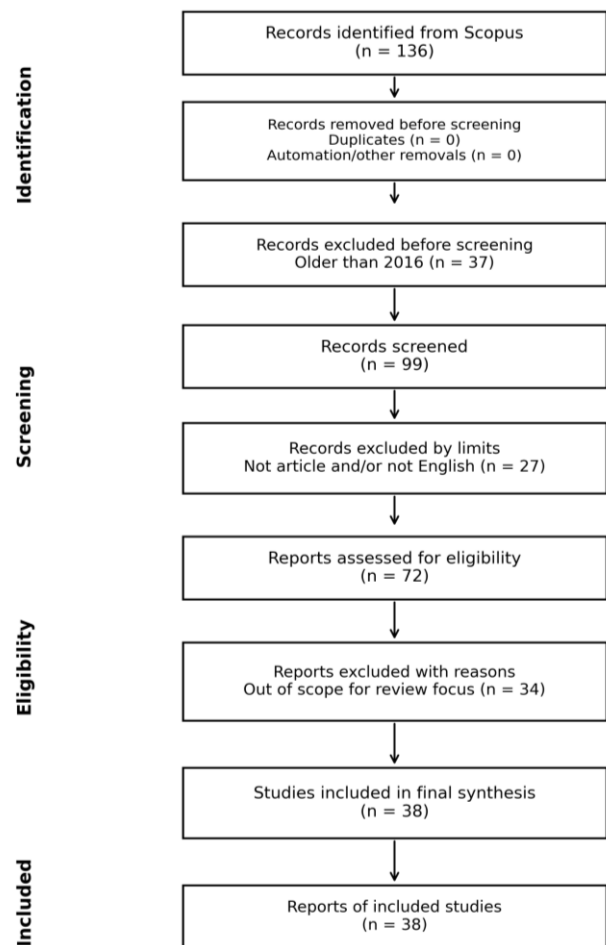


Figure 1. PRISMA flow diagram for study selection

Teacher competence is therefore both cognitive and contextual. It includes digital skills, science-specific technology knowledge, confidence, beliefs, motivation, design capacity, and opportunities for authentic classroom implementation. Professional development studies reinforce this point. Antonio & Prudente (2026) report significant gains in pre-service science teachers' TPACK and self-efficacy after a technology-integrated metacognitive argument-driven inquiry course. Kapıcı (2026) similarly shows that designing inquiry-based learning environments on a virtual platform and implementing them in real classrooms improved in-service science teachers' TPACK self-efficacy and practical skills. These studies position teacher competence as a developmental pathway rather than a fixed attribute.

Pedagogical Design and Technology-Mediated Science Learning

Digital technology becomes educationally meaningful only through pedagogical design. The same digital tool can support low-level presentation or high-level inquiry, depending on the learning objectives, task

structure, teacher scaffolding, student agency, and assessment design. Parker et al. (2019) argue that quality technology integration in science classrooms should be judged by its support for science and engineering practices, student-centered teaching, and contextualized learning. This moves the evaluation of technology beyond presence or frequency toward pedagogical quality.

Pedagogical reasoning is particularly important when teachers integrate emerging or visualization-intensive tools. Hsu et al. (2023) and Prahani et al. (2025) show that augmented reality integration in secondary biology required a teacher to redesign lessons, shift from didactic instruction toward inquiry-based teaching, and develop technological pedagogical and content knowledge through reflection. Rodríguez & Arévalo (2025) use TPACK and Activity Theory to show that technology-mediated learning activity design is shaped by contradictions among teacher knowledge, student characteristics, access, institutional rules, and learning goals. These studies suggest that technology integration should be viewed as iterative design rather than one-time adoption.

Constructivist and inquiry-based theories explain why digital tools can be powerful in science education. Simulations, virtual laboratories, augmented reality, interactive e-books, intelligent tutoring systems, and Web 2.0 tools can help students visualize invisible processes, test hypotheses, collect and analyze data, collaborate, and construct explanations. Computer-supported collaborative learning, for example, is grounded in the idea that social interaction and shared knowledge construction can deepen conceptual understanding. Ramirez (2021) shows that CSCL with question-asking scripts enhanced students' conceptual understanding and critical thinking. Uyar & Karamustafaoğlu (2025) demonstrate that Web 2.0-supported dialogic teaching in out-of-school settings can strengthen cognitive engagement and higher-order thinking.

Contextual Barriers, Equity, and Implementation Conditions

Theoretical interpretation also requires an ecological view of implementation. Digital technology integration is shaped by teachers, learners, school infrastructure, institutional leadership, curriculum policy, assessment culture, socioeconomic conditions, and ethical concerns. Turgut & Aslan (2021) synthesized ICT integration factors and identified students, educational materials, infrastructure, management, and teachers as interconnected influences. Their meta-synthesis indicates that integration cannot be solved by addressing one stakeholder or resource alone.

Equity conditions are particularly important in secondary science classrooms because digital tools may

either expand or restrict access to high-quality science learning. Rural schools, under-resourced public systems, and crisis-affected classrooms often face weak connectivity, insufficient devices, limited technical support, and reduced teacher training. Qashani & Boateng (2026) show that rural South African physical sciences classrooms experienced limited ICT use because of inadequate infrastructure, weak internet connectivity, insufficient training, and limited proficiency with digital tools. Mokhele-Ramulumo et al. (2024) report that the flipped classroom model in grade 12 physical science created opportunities for engagement but was constrained by access limitations and socioeconomic disparities.

Emerging technologies, including artificial intelligence and social media-based learning environments, represent additional examples of evolving digital practices that require careful pedagogical consideration. Lee & Zhai (2024) show that ChatGPT can support lesson planning, questioning, self-directed learning, and formative assessment, but also creates risks related to hallucinated materials and inappropriate visual guidance. Luong et al. (2023) and Zhang (2026) reports that social media integration in Chinese high-school science education increased participation and student-teacher interaction but raised concerns about unequal access, misinformation, and educator resistance. These findings show that digital integration requires ethical judgment, policy support, and culturally responsive implementation.

Figure 2 illustrates the integrated conceptual framework developed from the reviewed literature. The corresponding figures have been inserted into the revised manuscript. It places technology-integrated science pedagogy at the center and shows that meaningful digital integration depends on the interaction of four theoretical domains: technological pedagogical content knowledge, pedagogical reasoning and design, inquiry-based and constructivist science learning, and contextual and equity conditions. This framework reflects the review's central position that digital tools do not function as isolated instructional solutions. Instead, their educational value depends on teachers' ability to connect technology with science content, select appropriate pedagogical strategies, support inquiry and conceptual understanding, and respond to classroom realities. The outer factors, including teacher beliefs, self-efficacy, professional development, infrastructure, school support, student characteristics, curriculum constraints, and equity of access, further indicate that digital science teaching is an ecological process shaped by multiple interacting conditions.

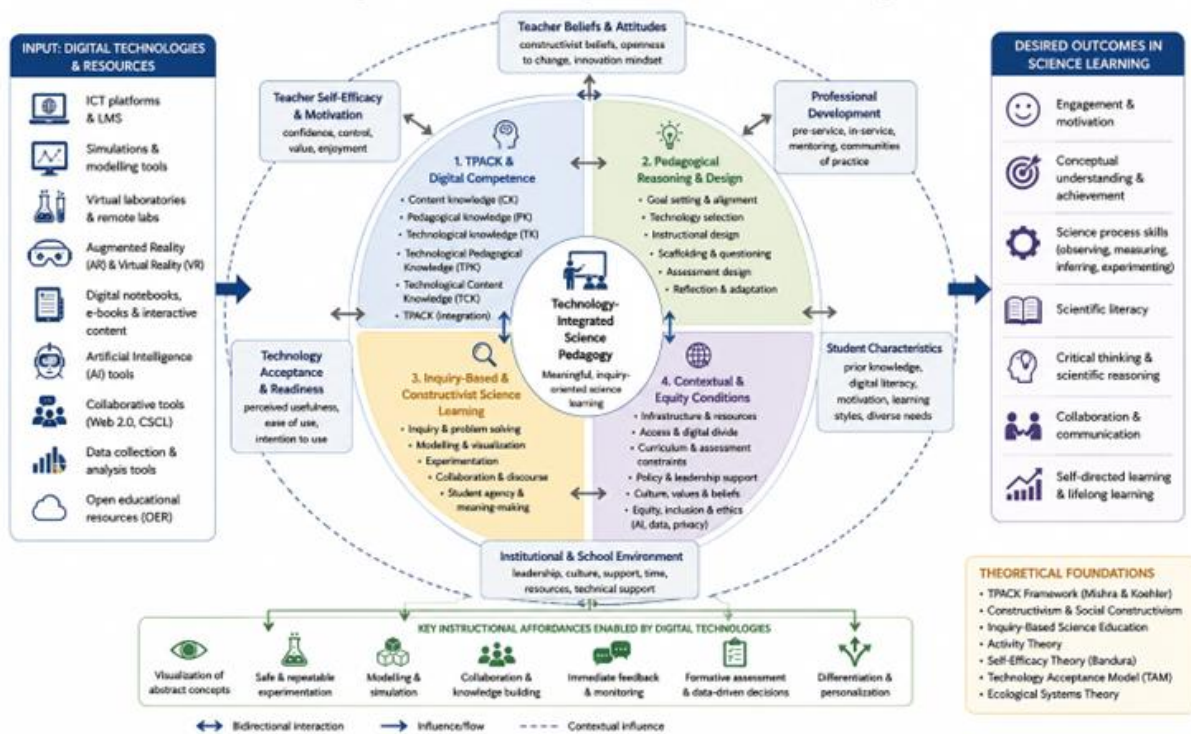


Figure 2. Integrated theoretical framework for digital technology integration in secondary school science learning

Results

The 38 studies included in the synthesis were organized into four analytic themes corresponding to the review questions: teacher competence and professional development; pedagogical design and classroom implementation; student learning outcomes and scientific competence; and barriers, enablers, and equity conditions. The tables below reproduce the extracted evidence matrix used to support the synthesis.

Teacher Competence, TPACK, and Professional Development in Digital Science Integration

Teacher competence emerged as a primary condition for meaningful digital integration in secondary science education. Table 1 shows that the teacher-focused evidence consistently moves beyond general digital literacy toward science-specific competence, TPACK, self-efficacy, and professional development. Abualrob & Al-Saadi (2025) demonstrate that TPCK and ICT teaching self-efficacy are central to teachers' valuation of ICT-enhanced science teaching, while Alegre & Galado (2023) show a positive relationship between technological competence and pedagogical content knowledge among junior high school science teachers. Chieng & Tan (2021) and Jita & Sintema (2022) identify gaps in teachers' technology-related knowledge, especially when compared with general pedagogical or content knowledge.

Figure 3 illustrates the developmental pathway through which science teachers move from basic digital

skills toward adaptive technology-supported science teaching. The pathway begins with operational digital skills but progresses toward science-specific technological knowledge, TPACK integration, pedagogical design capacity, reflective classroom implementation, and adaptive teaching. This progression is important because the reviewed literature shows that teachers may be able to use digital tools for presentation or documentation while still lacking the competence required to integrate simulations, virtual laboratories, augmented reality, modelling tools, or AI-supported resources into meaningful science inquiry. The figure also shows that professional development, mentoring, certification, collaborative practice, and reflective feedback can support this pathway, whereas low self-efficacy, inadequate training, limited modelling skills, traditional beliefs, and resource constraints can interrupt it. Thus, Figure 3 supports the argument that teacher competence is a central mechanism linking technology access to learning quality.

Several studies emphasize that competence develops through structured professional learning and authentic design practice. Mansour et al. (2024) show that TPACK among secondary STEM teachers is strongly associated with technological content knowledge and formal training. Alshorman & Aldaraghme (2025) highlight uneven digital skill profiles, with teachers more proficient in presentation and documentation than in simulation and modelling.

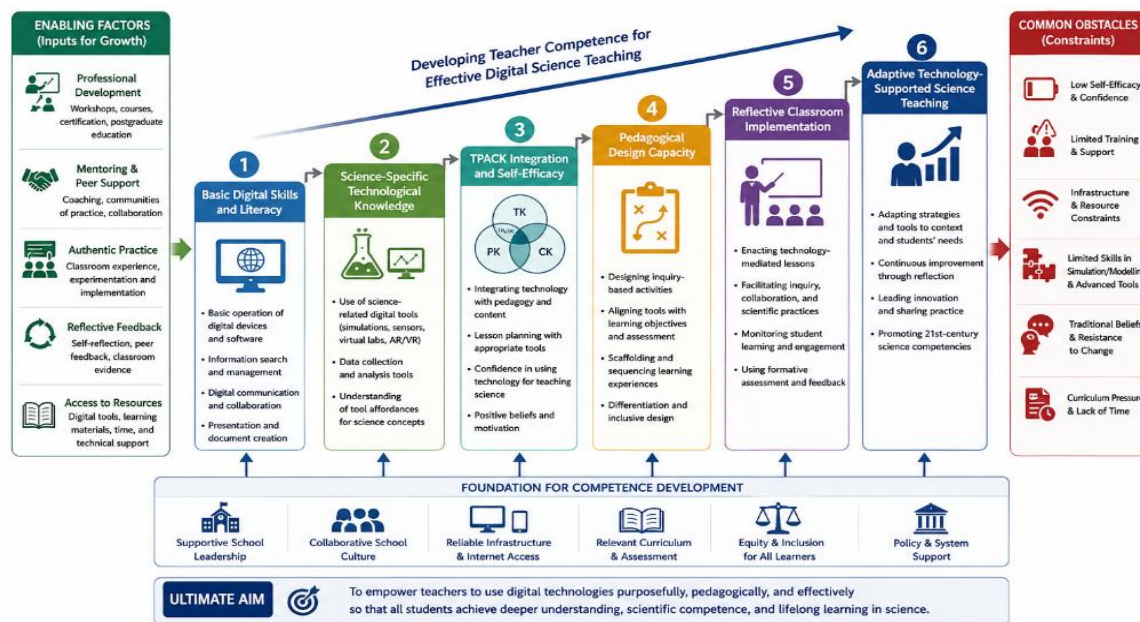


Figure 3. Teacher competence pathway for digital technology integration in secondary school science learning

Jere & Tsoka (2024) show that self-efficacy in simulation integration is shaped by experience and school socioeconomic factors. Kilty & Burrows (2021), Antonio & Prudente (2026), and Kapıcı (2026) collectively indicate that science teacher preparation

should connect coursework, inquiry-based design, classroom residency, and reflection. Overall, Table 1 indicates that teacher competence functions as a mediating mechanism between technology availability and instructional quality.

Table 1. Essential summary of findings on teacher competence, TPACK, and professional development in digital science integration

References	Country/context	Participants	Technology/framework	Research design	Key findings	Implications for secondary science learning
Abualrob & Al-Saadi (2025)	Science education; pre-service and in-service teachers	Science teachers	TPCK, ICT self-efficacy, enjoyment, control appraisal, value appraisal	Quantitative; structural equation modelling	ICT teaching self-efficacy, enjoyment, control appraisal, and TPCK significantly predicted teachers' perceived value of ICT integration.	Teacher training should strengthen TPCK and ICT self-efficacy through practical workshops, online courses, and collaborative activities.
Alegre & Galado (2023)	Junior high school science, Philippines	31 junior high school science teachers	Technological competence and PCK	Descriptive-correlational survey	Teachers showed high technological competence and high PCK practices, with a moderate positive correlation between the two.	Digital competence may enhance science teachers' PCK, but other pedagogical and contextual factors also influence effective teaching.
Chieng & Tan (2021)	Malaysian secondary science education	219 science teachers and 3 interviewees	TPACK and ICT integration	Sequential explanatory mixed-methods	Teachers' technology-related knowledge was lower than non-technology pedagogical and content knowledge. ICT use varied by tool type, pedagogy, content, and purpose.	Professional development should address technology-specific knowledge gaps among secondary science teachers.

References	Country/context	Participants	Technology/ framework	Research design	Key findings	Implications for secondary science learning
Jita & Sintema (2022)	Pre-service science teacher education	506 pre-service teachers; 28 interviewees	Technology Acceptance Model and TPACK	Mixed-methods	Pre-service teachers underestimated their competence to teach science with ICT. Technological knowledge was weaker than technological pedagogical knowledge. Internal TPACK components influenced external components, explaining 77% of variance in TPACK. TCK was especially influential.	Teacher education should develop technological content knowledge and strengthen confidence for ICT-supported science teaching. Structured training, certification, and postgraduate education can strengthen science teachers' TPACK integration.
Mansour et al. (2024)	Qatar secondary STEM education	245 science and mathematics teachers	TPACK; structural equation model	Quantitative SEM	Teachers reported high proficiency in presentation and documentation but lower scores in simulation and modelling. Public school teachers faced more barriers.	Subject-specific digital training and equitable resource allocation are needed for advanced science technology integration.
Alshorman & Aldaraghme (2025)	Jordanian science teaching	164 teachers and 14 interviewees	DiKoLAN digital competence framework	Mixed-methods	Teachers showed high self-efficacy in integrating simulations, but teaching experience and school socioeconomic factors significantly affected self-efficacy.	Teacher confidence must be supported by contextual resources, especially in rural and low-resource schools.
Jere & Tsoka (2024)	Rural South African science education	Rural science teachers	Simulation integration and self-efficacy	Survey-based quantitative study	Pre-service teachers used varied technologies during methods courses and residency, but strengths and weaknesses differed across implementation contexts.	Science teacher educators should prepare teachers to integrate technology for meaningful, not merely functional, learning.
Kilty & Burrows (2021)	Secondary science teacher preparationservice	Secondary science pre-service teachers	Technology Use in Science Instruction instrument	Collective case study	The course produced significant gains in perceived TPACK, personal efficacy, and outcome expectancy for inquiry-based teaching.	Theoretically grounded technology-integrated pedagogical courses can improve science teachers' competence and self-efficacy.
Antonio & Prudente (2026)	Philippine pre-service science teacher education	69 pre-service science teachers	Technology-integrated metacognitive argument-driven inquiry; TPACK	Intervention study with quantitative and qualitative analysis	Designing and implementing inquiry-based learning spaces improved teachers' TPACK self-efficacy, practical skills, and views on technology integration.	Professional development should connect virtual design with real classroom implementation.
Kapıcı (2026)	In-service 7th-grade science teacher education	11 in-service science teachers	Inquiry-based virtual platform; TPACK	Convergent mixed-methods		

Pedagogical Design and Classroom Implementation of Digital Technologies

Table 2 synthesizes evidence showing that digital technology integration is fundamentally a design problem. Agyei & Agyei (2021) propose ICT intervention features for Ghanaian senior high school physics that include sustainable ICT environments, teacher knowledge bases, inquiry-driven materials, and collaborative classroom arrangements. Apostolou (2020) challenges the assumption that 1:1 device access necessarily produces superior integration, showing that a limited PC-projector environment can support successful integration when the teaching approach is appropriate. These studies indicate that pedagogy and context mediate the value of infrastructure.

Figure 4 conceptualizes digital technology integration as an iterative pedagogical design cycle. The cycle begins with identifying a science concept and its associated learning difficulty, followed by selecting a content-specific digital tool, designing an inquiry-oriented or problem-based activity, implementing classroom interaction, assessing conceptual and process outcomes, and revising the activity based on reflection. This design cycle is consistent with the review's emphasis that technology integration should not be treated as a one-time decision to use a digital tool. Instead, teachers must align technological affordances with science content, learning objectives, student needs, and assessment evidence. Simulations, virtual laboratories, augmented reality, interactive e-books, computer-supported collaborative learning, intelligent tutoring systems, and AI-supported planning tools can support science learning only when they are embedded in coherent instructional designs. Figure 4 therefore clarifies why pedagogical design quality is essential for transforming digital tools into meaningful science learning experiences.

Design quality is also visible in studies of specific technologies. Hsu et al. (2023) show that augmented reality in secondary biology required iterative pedagogical reasoning and a shift toward inquiry-based teaching. López et al. (2025) found that content-specific technologies were associated with higher cognitive demand and scientific research skills, whereas Rodríguez & Arévalo (2025) warn that technology-mediated activities may still be designed with low cognitive demand. Lee & Zhai (2024) demonstrate both the opportunities and risks of ChatGPT-supported science lesson planning, especially the need to validate AI-generated content. Ormancı & Çepni (2020), Sarangi et al. (2023), Uyar & Karamustafaoğlu (2025), and Gunawan et al. (2020) further show that interactive e-books, online platforms, Web 2.0 tools, and intelligent tutoring systems can support science learning when they are aligned with curriculum goals, inquiry, higher-order thinking, and assessment. Thus, Table 2 shows that the design of learning tasks—not the novelty of tools—determines whether technology supports meaningful science learning.



Figure 4. Pedagogical design cycle for technology-mediated science learning

Table 2. Essential summary of findings on pedagogical design and classroom implementation of digital technologies in secondary science learning

References	Science subject/topic	Digital tool or strategy	Pedagogical approach	Implementation context	Main classroom findings	Design implications
Agyei & Agyei (2021)	Senior high school physics	ICT-based intervention	Interactive, learner-centered, inquiry-oriented teaching	Ghanaian senior high school physics classroom	Proposed intervention features included sustainable ICT environment, teacher ICT knowledge base, inquiry-driven materials, and collaborative arrangement.	ICT integration must be context-specific, content-specific, and aligned with interactive science teaching.
Apostolou (2020)	High school physics	ICT infrastructure: PC-projector versus 1:1 environment	ICT-supported teaching approach	Greek high school science classroom	ICT integration was equally successful in limited and high-infrastructure environments when the teaching approach was appropriate.	Pedagogical approach may matter more than device abundance in some secondary science classrooms.
Hsu et al. (2023)	Secondary biology	Augmented reality	Inquiry-based instructional redesign	Taiwanese secondary school	Teacher shifted from didactic to inquiry-based teaching and developed technological pedagogical and content knowledge through iterative reflection.	AR integration requires pedagogical reasoning, reflection, and iterative lesson redesign.
López et al. (2025)	Physics, chemistry, and biology	Content-specific technologies	Learning activity design	Pre-service science teacher education	Content-specific technologies were linked to higher cognitive demand and scientific research skills; TPACK correlated with integration quality.	Technology selection should be content-specific and designed to support scientific practices.
Rodríguez & Arévalo (2025)	Secondary science	Technology-mediated activities	TPACK and Activity Theory	Secondary science teacher activity design	Teachers selected content-specific technologies but often formulated low-cognitive-demand learning goals.	Pedagogical design must ensure that technology use supports high-level science learning, not only tool inclusion.
Lee & Zhai (2024)	Science lesson planning	ChatGPT	Generative AI-supported lesson planning	Pre-service elementary science teacher education	Lesson plans showed diverse ChatGPT applications, but some uses were inappropriate due to hallucinated materials and unsupported visual guidance.	AI integration requires critical validation, clear classroom roles, and pedagogical safeguards.
Ormancı & Çepni (2020)	Secondary science	Interactive e-book	Curriculum-aligned digital content	Three secondary schools in Türkiye	Teachers and students found interactive e-books useful, systematic, and visually engaging.	Interactive e-books can support structured science learning

References	Science subject/topic	Digital tool or strategy	Pedagogical approach	Implementation context	Main classroom findings	Design implications
						when aligned with curriculum objectives.
Sarangi et al. (2023)	Secondary science during COVID-19	Online platforms and digital pedagogy	Technology-pedagogy integration	Indian secondary science classes	ICT supported inquiry, cooperative learning, critical thinking, and multiple-format learning materials, but barriers included poor connectivity and reduced interaction.	Effective design requires infrastructure, teacher training, technical support, and student-centered pedagogy.
Uyar & Karamustafaoğlu (2025)	7th-grade science	Web 2.0 tools	Dialogic teaching and thought experiment	Out-of-school science learning environment	Web 2.0-supported dialogic teaching increased awareness of digital tools, cognitive engagement, and higher-order thinking.	Digital design can extend science inquiry beyond formal classroom settings.
Gunawan et al. (2020)	Junior secondary integrated science	Intelligent tutoring systems in blended learning	Lesson-plan development and higher-order thinking	Indonesian junior secondary science teachers	Teachers designed lesson plans that integrated technology, higher-order thinking, student-centered learning, and relevant assessment.	Intelligent tutoring systems can support teachers in designing blended science learning activities.

Student Learning Outcomes, Engagement, and Scientific Competence

Table 3 summarizes outcome-oriented studies and indicates that digital technology can support affective, cognitive, procedural, and social dimensions of science learning. Janous et al. (2022) report statistically significant improvement in achievement and motivation after ICT integration in life and earth sciences. Jiang et al. (2026), synthesizing 27 studies involving 2,839 students, found a moderate overall effect of ICT-assisted experiments in K-12 physics, with the strongest effect reported for skill outcomes. Ngema & Motlhabane (2025) show that virtual reality laboratory activities improved grade 10 learners' understanding of life sciences concepts and science process skills in rural schools. These studies provide evidence that digital tools can support both conceptual understanding and scientific practice.

Other studies refine this conclusion by showing that outcomes depend on learning design and learner characteristics. Baran et al. (2020) found that individual AR-assisted learning produced stronger attitudes toward AR than group use, though attitudes toward science courses did not significantly differ. Ramirez (2021) found that CSCL improved conceptual understanding and critical thinking, particularly when

supported by question-asking scripts. García-Perales & Palomares-Ruiz (2020) report that ICT-supported science teaching improved learning scores and motivation while also informing debates about the digital gender gap. Slemrod et al. (2023) and Tofel-Grehl et al. (2025) indicate that technology-supported vocabulary interventions may enhance engagement and accessibility among learners with learning difficulties, although they do not necessarily produce superior learning gains compared with conventional approaches. Chua et al. (2024), Alhashem & Alfaiakawi (2023), and Almasri (2022) further indicate that technology can support engagement and laboratory preparation, but sustained value depends on usability, perceived usefulness, and alignment with science goals. Table 3 therefore suggests that technology-supported outcomes are plural and should not be reduced to achievement alone.

Figure 5 maps the main learning outcomes associated with digital technology-supported science learning. The outcome clusters include engagement and motivation, conceptual understanding, science process skills, scientific literacy, critical thinking and reasoning, collaboration, and self-directed learning. The figure emphasizes that digital technology does not produce a single uniform learning effect; rather, different tools

tend to support different types of outcomes. For example, simulations and ICT-assisted experiments are especially relevant for conceptual understanding and procedural skills, virtual laboratories can support science process skills, augmented reality may strengthen visualization and engagement, and computer-supported collaborative learning can promote collaboration and

critical thinking when appropriately scaffolded. This outcome map helps organize the evidence reviewed in this section by distinguishing affective, cognitive, procedural, and social dimensions of learning. It also highlights the need for future studies to measure learning outcomes more precisely rather than relying only on general engagement or attitude indicators.

Table 3. Essential summary of findings on student learning outcomes, engagement, and scientific competence

References	Learner level	Technology used	Learning outcome measured	Method/instrument	Main results	Contribution to evidence
Janous et al. (2022)	Secondary students	ICT in life and earth sciences	Achievement, objectives, motivation	Experimental design with knowledge, achievement, and motivation tests	Experimental group showed statistically significant improvement in achievement and motivation, with $p < 0.0001$.	Provides evidence that ICT integration can improve both cognitive and motivational outcomes in secondary science.
Baran et al. (2020)	Fifth-grade students	Augmented reality for electrical circuits	Attitudes toward AR and science course	Two instructional designs; attitude measures, observations, interviews	Individual AR use produced significantly higher attitudes toward AR than group use; no significant difference in attitudes toward science course.	AR design may influence learner attitude differently depending on individual or group learning format.
Ngema & Motlhabane (2025)	Grade 10 learners	Virtual reality laboratory activities	Life sciences understanding and science process skills	Quasi-experimental design	Experimental group improved understanding and science process skills, including observation, interpretation, data measurement, data recording, and investigation planning.	Virtual labs can support both conceptual and procedural dimensions of science learning in rural schools.
Ramirez (2021)	Grade 7 students	Computer-supported collaborative learning with question-asking script	Conceptual understanding and critical thinking	Three-group pre-test-post-test quasi-experimental design	CSCL significantly improved conceptual understanding and critical thinking; scripting deepened discussion and comprehension.	Collaborative digital environments can enhance science reasoning when supported by structured questioning.
Jiang et al. (2026)	K-12 physics students	ICT-assisted experiments	Cognitive, affective, and skill outcomes	Meta-analysis of 27 studies involving 2,839 students	ICT-assisted experiments showed moderate overall effect, with $g = 0.463$; skill outcomes showed $g = 0.511$.	Provides strong quantitative evidence for ICT-assisted experiments in physics learning.
García-Perales & Palomares-Ruiz (2020)	Science students	ICT tools	Learning scores, motivation, gender-related outcomes	Pretest-posttest quasi-experimental method	ICT group showed higher motivation and better learning scores than control group; women scored higher than men in pretest and posttest.	ICT may support motivation and learning while also informing discussions of gender and science participation.

References	Learner level	Technology used	Learning outcome measured	Method/instrument	Main results	Contribution to evidence
Slemrod et al. (2023)	Secondary biology students with learning disabilities	Technology-based keyword mnemonics using iPod touch	Science vocabulary acquisition	Multiple treatment reversal design	Students acquired vocabulary equally well using technology and flash cards, but showed strong interest in technology-supported learning.	Technology may increase engagement and feasibility for students with disabilities, even when learning gains are comparable.
Chua et al. (2024)	School students across 35 schools	Sensor-based science education platform	Authentic sustained science technology use	Six-month large-scale evaluation; 1,245 students	Technology was useful when perceived as easy and valuable; integration should support learning goals rather than act as an end in itself.	Sustained implementation requires authentic classroom use and teacher-perceived value.
Alhashem & Alfaiakawi (2023)	Pre-service teachers preparing for middle/high school science	Virtual laboratories in chemistry	Engagement and attitudes toward laboratory learning	Experimental and control group survey	Virtual laboratory training improved attitudes, engagement, and understanding of educational methodologies before physical lab work.	Virtual labs can prepare future science teachers and support engagement in laboratory-based science learning.
Almasri (2022)	University science students	Computer simulations	Engagement, satisfaction, self-confidence, learning styles	Survey of 1,034 students	Students reported very high engagement and satisfaction; self-confidence and kinesthetic learning style predicted engagement and satisfaction.	Although higher education-based, it supports broader evidence that simulations can enhance engagement in science concepts.

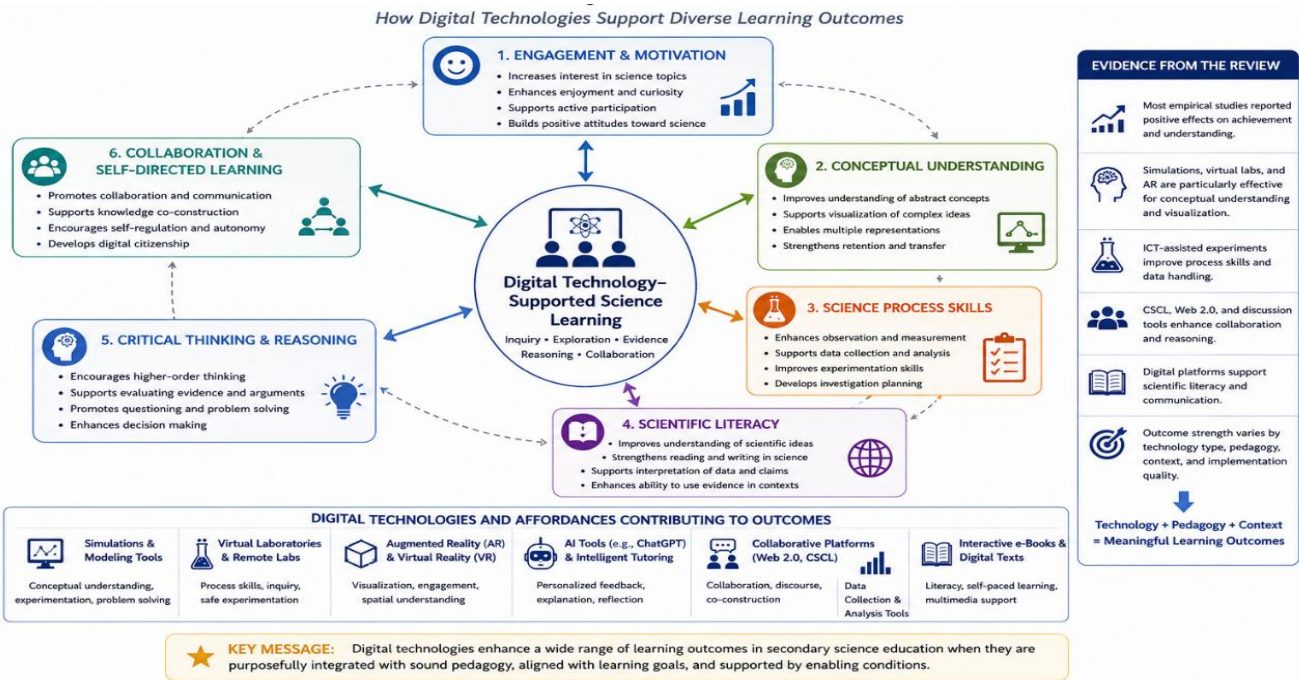


Figure 5. Learning outcome map of digital technology integration in secondary science education

Barriers, Enablers, and Equity Conditions in Digital Science Learning

Table 4 shows that barriers and enablers are distributed across teacher, student, school, and system levels. Qashani & Boateng (2026) identify limited infrastructure, inadequate training, weak internet connectivity, and limited tool proficiency as barriers in rural South African physical sciences classrooms. Yavuzalp & Öztürk (2026) extend this analysis by showing that infrastructure problems, software usability, curriculum constraints, traditional pedagogy, anxiety, and weak design capacity interact as primary, secondary, and third-order barriers. These findings caution against simplistic solutions that provide devices without addressing professional learning and systemic constraints.

Equity and sustainability are recurring concerns. Mokhele-Ramulumo et al. (2024) show that the flipped classroom model can support grade 12 physical science

engagement but is constrained by limited access, inadequate training, and socioeconomic disparities. Sarangi et al. (2023) and Gordy et al. (2021) show that technology-pedagogy integration during COVID-19 supported inquiry and flexible access, but also produced problems of attendance, connectivity, interaction, and health. Mashishi & Ramaila (2024), Mashishi et al. (2025), and Photo (2026) further indicate that technology integration in resource-constrained contexts depends on support, beliefs, reflective practice, and culturally grounded professional development. Zhang (2026) adds that social media integration can increase participation but requires safeguards against misinformation and unequal access. Apostolou (2020) and Turgut & Aslan (2021) reinforce the central conclusion of Table 4: sustainable digital integration requires systemic alignment among pedagogy, infrastructure, leadership, materials, equity, and teacher competence.

Table 4. Essential summary of findings on barriers, enablers, and equity conditions in digital science learning

References	Context	Barrier/enabler type	Specific challenge or support	Affected stakeholders	Reported consequences	Recommended response
Qashani & Boateng (2026)	Rural South African physical sciences classrooms	Infrastructure, training, proficiency, policy support	Limited ICT use, inadequate training, weak internet connectivity, limited proficiency with tools	Teachers and learners	ICT benefits were constrained by rural infrastructure and limited teacher capacity.	Improve ICT training, infrastructure, and policy support for rural high schools.
Yavuzalp & Öztürk (2026)	Turkish science education	Primary, secondary, and third-order barriers	Infrastructure problems, software usability, curriculum constraints, traditional pedagogy, anxiety, and weak design capacity	Science teachers	Barriers interacted systemically and limited e-argumentation software implementation.	Build supportive ecosystems that address infrastructure and pedagogical design capacity together.
Mokhele-Ramulumo et al. (2024)	South African grade 12 physical science during crisis	Access, training, socioeconomic inequality	Limited access, inadequate training, file-size limits, weak digital infrastructure	Teachers and learners	Flipped classroom model improved engagement but was constrained by digital inequality and crisis conditions.	Combine technological and non-technological resources with sustained professional development.
Sarangi et al. (2023)	Indian secondary science during COVID-19	Infrastructure, management, teacher readiness	Poor attendance, poor connectivity, health concerns, limited face-to-face interaction	Teachers and students	Technology supported learning flexibility but created participation and interaction challenges.	Strengthen infrastructure, school support, and teacher preparation for technology-integrated pedagogy.
Mashishi & Ramaila (2024)	Life sciences classrooms	Resource limitation, support, logistical issues	Limited familiarity with Scratch, resource constraints, inadequate teacher support, load shedding	Pre-service teachers and learners	Scratch supported active learning but implementation was limited by	Provide resources, teacher support, and strategic interventions for coding-supported science learning.

References	Context	Barrier/enabler type	Specific challenge or support	Affected stakeholders	Reported consequences	Recommended response
Mashishi et al. (2025)	South African secondary agricultural sciences	Teacher beliefs and technology-mediated assessment	Initial skepticism toward simulations and technology-mediated assessment	Agricultural science teachers	resource and support barriers. Beliefs shifted positively after observing improved learner engagement and comprehension.	Use professional development and reflective practice to transform beliefs about technology integration.
Photo (2026)	Rural South African STEM education	Rural constraints, Indigenous knowledge integration, teacher empowerment	Limited resources and contextual constraints	Rural teachers and learners	Teachers became more confident and agentive through sustained professional development.	Use contextually grounded, reflective PD to support culturally relevant and technology-supported science learning.
Zhang (2026)	Chinese high-school science education	Cross-cultural access, misinformation, resistance	Unequal access, misinformation risk, educator resistance to technology-centered methods	High school students and teachers	Social media increased participation and interaction but raised equity and reliability concerns.	Prioritize equitable access, culturally tailored professional development, and misinformation safeguards.
Apostolou (2020)	Greek high school science teaching	Infrastructure level	Comparison between low-resource PC-projector and 1:1 computer environments	Students and science teacher	Similar integration success occurred under both infrastructure conditions when pedagogy was appropriate.	Avoid assuming that more devices automatically produce better integration; focus on teaching design.
Turgut & Aslan (2021)	ICT integration in Turkish education	System-level factors	Student competence, materials, infrastructure, management, teacher competence, technical support	Students, teachers, administrators	ICT integration was shaped by interconnected stakeholder and system factors.	Address ICT integration holistically across students, teachers, infrastructure, management, and materials.

Figure 6 supports this section by representing technology integration as an ecological process shaped by multiple interacting conditions. Also, Figure 6 presents an ecological model showing that digital technology integration in secondary science learning is shaped by interacting barriers and enablers across teacher, student, school, and system levels. At the teacher level, TPACK, self-efficacy, beliefs, design capacity, and professional development influence whether digital tools are used meaningfully. At the student level, access, motivation, prior knowledge, digital skills, and participation shape learning

opportunities. At the school level, infrastructure, internet connectivity, technical support, leadership, and resources affect implementation feasibility. At the system level, curriculum policy, equity, socioeconomic conditions, rural-urban differences, AI ethics, and misinformation concerns shape broader sustainability. Figure 6 therefore supports the review’s argument that technology integration cannot be improved through device provision alone. Sustainable and equitable digital science learning requires coordinated support across classroom practice, teacher development, school infrastructure, and education policy.

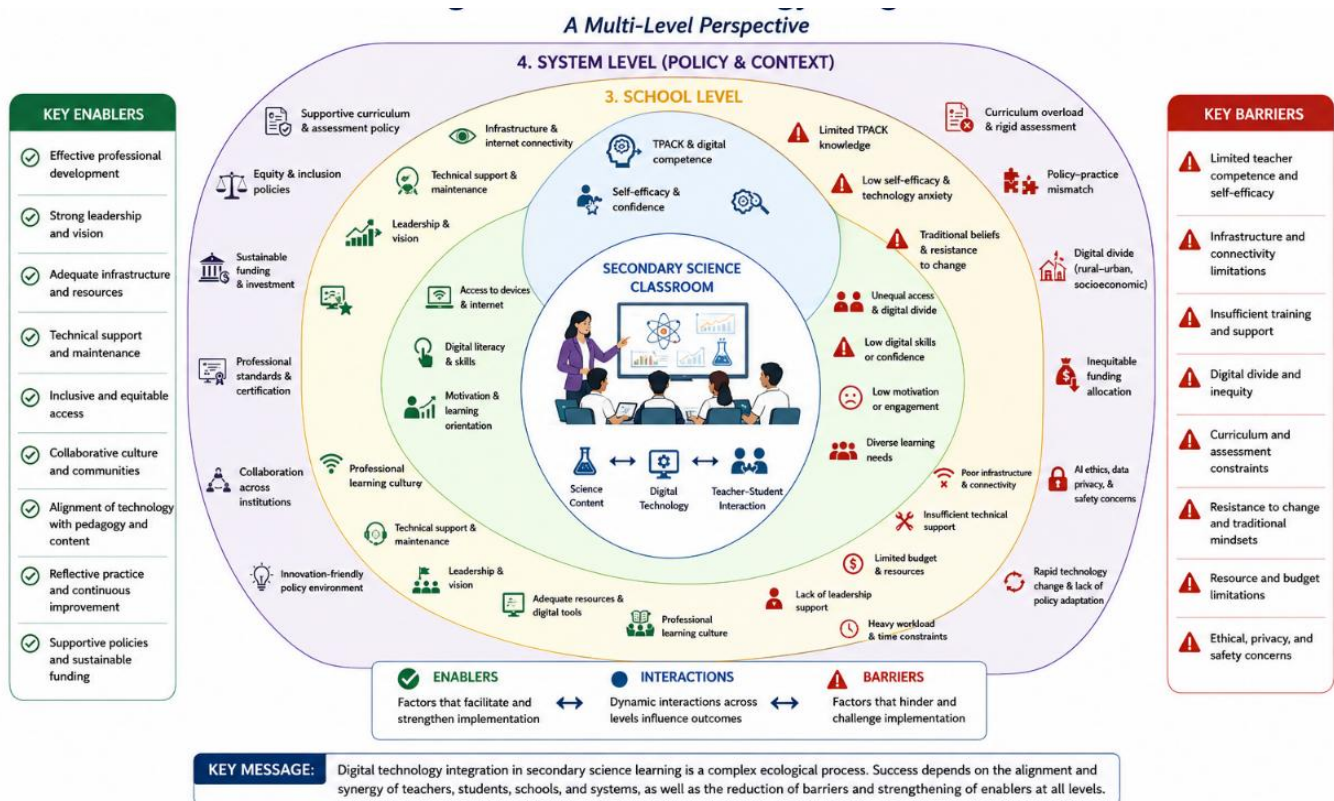


Figure 6. Ecological model of barriers and enablers in digital science learning

Discussion

The synthesis demonstrates that digital technology integration in secondary school science learning should be understood as an interaction among teacher competence, pedagogical design, learner engagement, and contextual support. Technology itself does not directly improve science learning. Instead, learning gains emerge when teachers use digital tools to represent scientific concepts, support inquiry, structure collaboration, scaffold reasoning, assess understanding, and connect classroom activity with scientific practices. This interpretation is consistent with the teacher competence evidence in Table 1 and the design evidence in Table 2: TPACK, self-efficacy, technological content knowledge, and reflective design capacity mediate the relationship between technological resources and classroom value.

The findings extend the TPACK framework by showing that technology integration is not only a knowledge configuration inside the teacher, but also an ecological practice shaped by infrastructure, access, curriculum, assessment, leadership, and equity. Abualrob & Al-Saadi (2025), Chieng & Tan (2021), Jita & Sintema (2022), Mansour et al. (2024), and Alshorman & Aldaraghme (2025) show that teachers require more than confidence with digital devices. They need science-specific knowledge of how digital tools transform

content, support visualization, enable experimentation, and structure inquiry. At the same time, Qashani & Boateng (2026), Mokhele-Ramulumo et al. (2024), and Yavuzalp & Öztürk (2026) show that even competent teachers may be constrained by weak infrastructure, insufficient training, software limitations, curriculum pressure, and digital inequality.

Pedagogical design is the bridge between competence and outcomes. Studies of AR, simulations, virtual laboratories, CSCL, Web 2.0 tools, interactive e-books, intelligent tutoring systems, and AI-supported lesson planning show that digital technologies differ in affordances and risks. For example, Hsu et al. (2023) and López et al. (2025) demonstrate that content-specific technologies can support inquiry and scientific research skills when integrated through deliberate design. In contrast, Rodríguez & Arévalo (2025) reveal that technology-mediated learning activities can remain cognitively weak if learning goals are not ambitious. This explains why similar technologies may produce different outcomes across contexts: the decisive factor is not the tool alone, but the designed relationship among tool, task, content, teacher mediation, and learner activity.

The outcome evidence is encouraging but should be interpreted with methodological caution. Janous et al. (2022), Jiang et al. (2026), Ngema & Motlhabane (2025),

Ramirez (2021), and García-Perales & Palomares-Ruiz (2020) show positive associations between digital technology and achievement, motivation, science process skills, conceptual understanding, and critical thinking. Yet outcome measures vary considerably across studies, and many interventions are short-term, context-specific, or dependent on teacher support. Engagement gains are often easier to document than durable conceptual change. This suggests that future research should distinguish affective outcomes, cognitive outcomes, procedural skills, scientific literacy, and collaborative competence rather than treating learning as a single outcome category.

The review also clarifies that equity must be treated as a core dimension of technology integration rather than an external implementation issue. Rural schools, crisis-prone classrooms, students with disabilities, and resource-limited systems can benefit from digital tools, but only when access, usability, training, and support are addressed. Slemrod et al. (2023) show that technology-based vocabulary intervention may support engagement among students with learning disabilities, while Photo (2026) illustrates how technology can be integrated with Indigenous knowledge through sustained professional development. However, unequal access, weak connectivity, misinformation, and AI-related risks can reproduce or intensify existing inequalities. Therefore, technology integration in science education must be accompanied by equity-sensitive policy and ethical guidance.

The review's theoretical contribution is an integrated model of digital science learning in which teacher competence, pedagogical design, student learning processes, and contextual conditions operate together. The practical implication is that schools and teacher education programs should move away from generic digital-skills training and toward content-specific, classroom-embedded professional development. Training should help science teachers select appropriate tools, design inquiry tasks, assess scientific reasoning, use data and feedback, and adapt instruction to diverse learners. Policy should prioritize not only devices and connectivity but also technical support, time for collaboration, curriculum flexibility, and evaluation of pedagogical quality. The main limitations of the review are the reliance on the supplied search log, the heterogeneity of included study designs, the restriction to English-language journal articles, and the absence of independently recalculated risk-of-bias ratings. These limitations should be addressed in future review updates using complete database exports, full-text appraisal forms, and more fine-grained outcome coding.

Conclusion

This systematic review synthesized evidence on digital technology integration in secondary school science learning through the interrelated lenses of teacher competence, pedagogical design, student learning outcomes, and implementation conditions. The findings indicate that digital tools can support engagement, motivation, conceptual understanding, scientific literacy, science process skills, critical thinking, collaboration, and self-directed learning. However, these benefits depend on teachers' TPACK, self-efficacy, design capacity, instructional alignment, and contextual support. Technology integration is therefore best understood as a pedagogical and ecological process rather than a technical intervention. The review contributes an integrated framework in which digital technologies become meaningful when they are aligned with science content, inquiry-based pedagogy, assessment, learner needs, and equitable classroom conditions. The evidence also shows that infrastructure, professional development, leadership, curriculum flexibility, and policy support are essential for sustainable implementation. Future research should provide stronger longitudinal evidence, evaluate durable conceptual and procedural outcomes, examine rural and under-resourced settings more closely, and develop ethical guidance for AI-supported science learning. Digital technology should be treated as a pedagogical amplifier: it enhances science learning only when teachers and systems deliberately align tools with scientific concepts, inquiry practices, and students' real learning needs.

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Author Contributions

Conceptualization, data collection, writing—original draft preparation, Y.H. and R.R.; analysis, R.R.; writing and editing, Y.H., R.R., and W.W.; supervision, E.K. and W.W. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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