EP-JOURNALS

GLOBAL JOURNAL OF EDUCATION, FINANCE & MANAGEMENT

Available on: https://gjefm.ep-journals.org/ E-ISSN: 3117-6771, P-ISSN: 3117-6763

Global Journal of Education, Finance and Management

Volume: 02 Issue: 05 May-2026

Digital Technologies in Science Education: Interactive Simulations, Virtual Laboratories, And Pedagogical Transformation

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Published Date: May 25, 2026 **DOI: 10.65150/EP-gjefm/V2E5/2026-02**

ABSTRACT: Digital technologies expand how students visualize, investigate, and model complex scientific phenomena. This integrative review synthesizes recent international research on non-AI digital technologies in science education, with emphasis on interactive simulations, virtual laboratories, augmented and virtual reality environments, and mobile measurement tools. The review examines evidence from physics, chemistry, biology, and related domains, focusing on learning outcomes, inquiry-based pedagogy, teacher professional development, and ethical-policy implications. The reviewed literature suggests that these technologies can support conceptual understanding, engagement, access to experimental experiences, and authentic data-based inquiry, particularly when embedded in guided inquiry, structured reflection, and curriculum-aligned activities. However, their effectiveness depends on instructional design, teacher expertise, infrastructure, accessibility, and institutional support. The review also identifies persistent challenges related to digital equity, data privacy, platform dependency, intellectual property, and environmental sustainability. Its main contribution is to connect evidence about learning outcomes with the professional and policy conditions required for responsible implementation. The article argues that digital technologies should not be treated as stand-alone solutions but as pedagogical resources whose value depends on thoughtful integration, equitable access, and responsible governance. These lessons are especially important as science education systems prepare for future AI-enhanced tools and learning environments.

KEYWORDS: digital technologies; interactive simulations; virtual laboratories; augmented reality; science education.

1. INTRODUCTION

Over the past decade, science education has undergone a profound digital transformation. Interactive simulations, virtual laboratories, augmented reality (AR) and virtual reality (VR) environments, mobile sensors, and collaborative cloud platforms are reshaping how physics, chemistry, biology, and earth sciences are taught and learned. These tools enable students to explore complex phenomena safely, conduct experiments beyond the limits of traditional school laboratories, and engage in inquiry-based learning that supports deeper conceptual understanding. For teachers, digital technologies open opportunities to redesign instruction, integrate new forms of representation, and rethink the relationships among experiment, theory, and modelling that lie at the heart of scientific reasoning.

This shift accelerated during the COVID-19 pandemic, when emergency remote teaching forced rapid adoption of digital tools across education systems. Although the pandemic created severe pedagogical disruption, it also normalized practices previously confined to a minority of innovative classrooms, including online simulations, screen-shared inquiry tasks, smartphone-based measurements, and asynchronous laboratory activities. Several years after the return to in-person teaching, many of these practices have persisted, and large surveys of university physics laboratory instructors across Europe report that smartphones, tablets, video analysis tools, and digital measurement instruments are now part of the regular methodological repertoire of higher-education science (Lahme et al., 2023). At the same time, post-pandemic research has documented uneven access, fragile teacher preparation, and growing concerns about data, privacy, and equity that complicate any simple narrative of progress (Gottschalk & Weise, 2023; UNESCO, 2023).

Among non-AI digital tools, interactive simulations have emerged as the most widely implemented strategy in science classrooms. A recent meta-analysis of PhET Interactive Simulations reported consistent improvements in students' conceptual understanding across physics topics, with effect magnitudes shaped by instructional context and learner characteristics; simulations were most effective when embedded in inquiry-oriented or guided-discovery sequences rather than used as supplementary demonstrations (Tene et al., 2024; Ramaila, 2024). Evidence from elementary contexts supports these findings: short interventions on topics such as solubility and the particulate nature of matter enhance pupils' scientific reasoning compared with traditional instruction (Diab et al., 2024). Comparable results have been reported in junior secondary schools in Nigeria (Olugbade et al., 2024) and Malawi (Banda & Nzabahimana, 2023), where simulation-based learning improved both achievement and motivation in oscillations, waves, and basic mechanics.

Virtual laboratories (VLs) extend simulation affordances toward more procedurally complete experimentation. In a mixed-methods study of life-science teachers in rural South Africa, participants expressed strong positive perceptions of VLs as a way to overcome geographic and resource constraints, while also identifying technical infrastructure and professional support as the key conditions for sustainable adoption (Shambare & Jita, 2025). A 2024 meta-analysis of virtual laboratories in engineering education, drawing on 46 studies, reported positive effects of VLs on student performance relative to traditional laboratory instruction, with effects varying according to context, discipline, level of study, and instructional design. The evidence suggests that VLs are most beneficial when paired with explicit reflection, guided inquiry tasks, or complementary face-to-face laboratory experiences. A systematic review of virtual labs across the natural sciences identified medium effect sizes ($g \approx 0.59$) and noted increased adoption across chemistry, biology, and physics in both K–12 and tertiary settings (Santos & Prudente, 2022; Pang et al., 2025).

AR and VR technologies represent a third and rapidly evolving family of tools. A 2024 systematic review of immersive educational technologies in medical and radiation physics, drawing on 37 studies, found that AR, VR, and mixed-reality (MR) applications have been associated with improvements in engagement, three-dimensional spatial reasoning, and procedural skill acquisition. However, the strength and durability of these effects remain dependent on instructional design, implementation quality, hardware access, and learner characteristics. These technologies also raise concerns about hardware cost, scalability, accessibility, and ergonomic factors such as motion sickness. A broader review of immersive technologies in STEM education identified rapid growth in published studies between 2019 and 2023, accompanied by persistent gaps in long-term outcome data and equity-sensitive design (Tene, García, et al., 2024).

Despite these advances, important challenges remain. Persistent infrastructure inequalities, uneven teacher professional development, and tensions between traditional hands-on practices and digital approaches can limit effective integration (Shambare & Jita, 2025). Some empirical literature is constrained by small samples, short-term designs, or quasi-experimental approaches that limit causal inference. Moreover, the growing role of commercial vendor platforms raises new questions about student data protection, ownership of learning analytics, and long-term lock-in effects (Jarke & Breiter, 2019; UNICEF, 2024). The literature also remains fragmented: many studies examine simulations, virtual laboratories, AR/VR environments, or mobile measurement tools separately, often focusing on learning outcomes, teacher adoption, or technical implementation in isolation. Less attention has been given to how these technologies collectively reshape science learning, teacher professional development, and educational policy. This gap matters because the educational value of digital tools cannot be understood only through measures of achievement or engagement; it depends on instructional design, teacher expertise, infrastructure, equity, privacy, sustainability, and platform governance.

For the purposes of this review, non-AI digital technologies are defined as digital tools whose core pedagogical function does not depend on machine learning, generative artificial intelligence, adaptive algorithms, or automated decision-making. This category includes interactive simulations, virtual laboratories, AR/VR environments, mobile measurement tools, and collaborative digital platforms when their instructional role is based primarily on visualization, manipulation, experimentation, communication, or data collection. Because many contemporary platforms include some analytics, automated feedback, or dashboards, borderline cases were treated cautiously. Tools were included when these features were peripheral and the main pedagogical activity remained teacher-directed exploration, simulation, experimentation, representation, or data collection. Tools were excluded when the central educational mechanism depended on AI-driven personalization, machine-learning prediction, automated assessment, recommender systems, or generative AI output. This distinction maintains the conceptual focus on the “digital but pre-AI” generation of educational technologies, while acknowledging that the boundary is becoming increasingly fluid.

This article synthesizes recent international research on non-AI digital technologies in science education, focusing on interactive simulations, virtual laboratories, and AR/VR applications, together with mobile measurement tools and collaborative platforms. The review aims to (a) clarify the pedagogical impacts of these technologies in physics and related sciences; (b) identify requirements for effective teacher professional development; and (c) highlight key ethical and policy challenges in an era of intensifying digital transformation. Accordingly, the review is guided by the following research questions:

RQ1. What pedagogical benefits and limitations are associated with interactive simulations, virtual laboratories, immersive AR/VR environments, and mobile measurement tools in science education?

RQ2. What forms of teacher professional development appear most effective for supporting the meaningful integration of these technologies into science teaching?

RQ3. What ethical, infrastructural, and policy challenges shape the equitable and sustainable use of non-AI digital technologies in science education?

The article therefore concentrates on the “digital but pre-AI” generation of educational technologies, while recognizing that lessons learned from these tools will shape how educators and policymakers respond to the next wave of AI-driven systems. The contribution of this review is threefold. First, it brings together evidence on interactive simulations, virtual laboratories, immersive AR/VR environments, and mobile measurement tools, which are often reviewed separately. Second, it connects learning outcomes with the professional conditions required for effective classroom implementation, especially teacher professional development and TPACK-informed instructional design. Third, it situates digital technology integration within wider ethical and policy debates concerning equity, privacy, platform governance, open access, and environmental sustainability. In doing so, the review offers an integrated framework for understanding digital transformation in science education as a pedagogical, professional, and systemic process.

2. METHODOLOGY

This article follows an integrative review approach designed to capture and synthesize recent empirical and theoretical research on non-AI digital technologies in science education. An integrative review was chosen because it allows the inclusion of both quantitative and qualitative studies and supports the development of a comprehensive understanding of emerging trends in a field where research designs, contexts, and outcome measures vary widely (Torraco, 2016; Whittemore & Knafl, 2005). The goal was not only to summarize findings but also to identify conceptual patterns and pedagogical implications relevant to interactive simulations, virtual laboratories, and immersive environments.

A systematic search was conducted between January and March 2025 across four major databases: Scopus, Web of Science, ERIC, and Education Source. To ensure coverage of physics-specific research, searches also included the Physical Review Physics Education Research database and selected open-access journals such as Education Sciences, Smart Learning Environments, the Journal of Science Education and Technology, Computers & Education, and Frontiers in Education. Search strings combined key terms such as digital technologies, interactive simulations, virtual laboratory, augmented reality, virtual reality, science education, and physics education, using Boolean operators and truncations. The initial time frame was January 2019 to December 2024. A supplementary update search identified highly relevant studies and policy documents published in 2025 and early 2026; because these sources were very recent, they were checked carefully for publication status, DOI accuracy, journal or publisher information, and relevance. Seminal earlier studies were included when necessary for conceptual grounding, such as foundational work on TPACK and teacher beliefs.

Studies were included if they (a) focused on primary, secondary, or tertiary science education, with particular interest in physics; (b) investigated digital tools other than artificial intelligence as a primary object of inquiry; (c) reported empirical findings or theoretical analyses relevant to pedagogy, learning outcomes, teacher professional development, or policy; and (d) were published in peer-reviewed journals or conference proceedings in English. Studies were excluded if they centred primarily on AI algorithms, machine-learning systems, or purely technical hardware development without an explicit educational application. Two reviewers independently screened titles and abstracts for relevance and resolved discrepancies through discussion (Whittemore & Knafl, 2005). Where studies fell on the border of AI and non-AI technologies—for example, simulations with adaptive prompts or learning analytics dashboards—we included them when AI components were ancillary rather than central to the pedagogical claim and explicitly flagged this in the synthesis.

The review followed a staged screening procedure. Records were first identified through database and supplementary journal searches; duplicates were removed before title and abstract screening. Titles and abstracts were screened against the inclusion criteria, and studies that did not focus on science education, did not examine digital technologies as educational tools, or centred primarily on AI-based systems were excluded. Full texts of potentially relevant studies were then assessed for eligibility. The final corpus included empirical studies, systematic reviews, meta-analyses, and policy documents that directly informed the synthesis. Although the review did not conduct a formal meta-analysis, quantitative indicators such as effect sizes were recorded when available and used cautiously to support the interpretation of trends.

For each study, data were extracted on research context, including educational level, country, subject domain, type of digital technology, research design, participant characteristics, key findings, and reported limitations. To facilitate thematic synthesis, findings were first organized according to the main type of technology examined: interactive simulations, virtual laboratories, immersive AR/VR environments, and mobile measurement tools. Mobile measurement tools were treated as a cross-cutting category because they often appear in combination with simulations, virtual laboratories, or collaborative platforms (Lahme et al., 2023). In a second stage, the studies were compared across categories to identify recurring pedagogical and institutional themes, including inquiry-based learning, conceptual change, student engagement, teacher guidance, teacher beliefs, professional development, equity, infrastructure, privacy, and sustainability. A constant-comparison approach was used to examine similarities and differences across technologies, educational levels, science domains, and research designs (Corbin & Strauss, 2015).

To clarify the composition of the corpus, included sources were categorized according to their primary focus: interactive simulations, virtual laboratories, immersive AR/VR environments, mobile measurement tools, teacher professional development, and ethical-policy issues. Some sources contributed to more than one category, particularly studies that connected digital tools with inquiry-based learning, teacher professional development, or equity concerns. This categorization ensured that the synthesis did not treat digital technologies as isolated tools but examined them in relation to pedagogical design, teacher expertise, and institutional conditions. To strengthen interpretive reliability, methodological quality and relevance were considered during analysis. Greater weight was given to systematic reviews, meta-analyses, well-designed experimental or quasi-experimental studies, and studies that clearly described participants, intervention design, outcome measures, and limitations. Studies with small samples, short interventions, or weak reporting were used more cautiously, mainly to illustrate emerging trends rather than to support strong causal claims. Policy documents were used primarily to contextualize issues of equity, privacy, infrastructure, and sustainability.

This integrative review has several limitations. First, although it followed a structured search and screening process, it was not designed as a formal systematic review or meta-analysis; its purpose is to synthesize recurring patterns, conceptual relationships, and pedagogical implications rather than to provide exhaustive coverage or statistically aggregated estimates of effectiveness. Second, the heterogeneity of study designs, instructional contexts, technologies, and outcome measures prevents direct comparison of effect sizes; reported effect sizes were therefore used only as indicators of general trends. Third, many studies in this field rely on short-term interventions, small samples, or quasi-experimental designs, limiting claims about long-term retention, transfer, and causal impact. Fourth, the restriction to English-language publications may have excluded relevant research from Spanish-, Portuguese-, Chinese-, Arabic-, and other non-English-speaking research communities. Finally, the rapid pace of technological change means that findings related to specific platforms, devices, or software versions may become outdated more quickly than broader pedagogical principles. For this reason, the synthesis emphasizes recurring pedagogical, professional, ethical, and policy-level patterns rather than claims tied to particular products.

3. RESULTS AND DISCUSSION

The results are organized in relation to the three research questions. Section 3.1 addresses RQ1 by synthesizing the pedagogical benefits and limitations of interactive simulations, virtual laboratories, immersive AR/VR environments, and mobile measurement tools. Section 3.2 addresses RQ2 by examining the forms of teacher professional development that support meaningful digital integration, with particular attention to TPACK, teacher beliefs, and collaborative professional learning. Section 3.3 addresses RQ3 by discussing the ethical, infrastructural, and policy challenges

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that shape the equitable and sustainable use of digital technologies in science education. Section 3.4 draws together implications for research, classroom practice, teacher education, and policy.

3.1 Digital Technologies in Science Education

The growing diversity of digital technologies in science classrooms reflects both advances in educational software and the increasing accessibility of high-speed internet, portable devices, and cloud services. Within physics and related sciences, three categories of digital innovation have attracted particular research attention: interactive simulations, virtual laboratories, and immersive AR/VR environments. These tools share the common goal of making scientific concepts visible, manipulable, and amenable to experimentation, but each provides distinct affordances for inquiry, representation, and conceptual change. A fourth, increasingly important category—mobile measurement and sensing tools—cuts across the others and deserves separate consideration.

3.1.1 Interactive Simulations

Interactive simulations are the most established of these tools. Platforms such as PhET Interactive Simulations, GeoGebra, Algodoo, oPhysics, and the Open Source Physics collection provide students with opportunities to explore relationships among variables, test hypotheses, and visualize abstract concepts such as wave interference, electromagnetic fields, quantum tunnelling, and chemical equilibrium. Their pedagogical strength lies in supporting exploratory and inquiry-based learning that is often difficult to implement in conventional classroom settings, particularly when phenomena are invisible, too fast, too slow, too dangerous, or too costly to reproduce physically (Meletiou-Mavrotheris & Paparistodemou, 2025; Pang et al., 2025).

Recent experimental and quasi-experimental studies suggest that carefully designed simulations and virtual physics experiments can support learning gains, particularly when integrated into inquiry-based instruction. Evidence from primary science education also shows that virtual physics experiments can produce learning outcomes comparable to, and in some cases stronger than, real experiments when students investigate concepts such as frictional force (Evangelou & Kotsis, 2019). In a multi-country quasi-experimental program involving secondary physics classes, students using PhET simulations achieved higher post-test scores on topics including energy conservation, electricity, and waves, and reported greater engagement compared with peers receiving lecture-based instruction (Banda & Nzabahimana, 2021). A 2024 meta-analysis synthesizing PhET-based interventions reported a positive overall effect on learning outcomes, but also indicated that the magnitude depends strongly on instructional design, including whether simulations are used for guided exploration, prediction-and-test cycles, collaborative reasoning, or merely as illustrations (Tene et al., 2024). Comparable benefits have been reported in chemistry and biology, especially when simulations are paired with collaborative problem solving, structured prediction tasks, and teacher-led reflection (Moore et al., 2013). The evidence therefore supports the pedagogically guided use of simulations rather than the assumption that simulations automatically improve learning.

The effectiveness of simulations is mediated by teacher guidance and by the inclusion of reflective questions, peer discussion, and explicit links to canonical concepts. Pranata (2024) demonstrated in a quasi-experimental study that game-based use of PhET in chemical equilibrium produced significant gains in both understanding and motivation, but only when students were scaffolded through structured worksheets rather than left to free-play. Olugbade et al. (2024), working with Nigerian junior secondary students, reported that PhET-supported instruction enhanced learning outcomes in basic science and technology, emphasizing that integration into well-defined instructional sequences was a precondition for measurable gains. These findings reinforce a recurring conclusion: digital tools function best when embedded in structured pedagogical frameworks rather than treated as stand-alone resources (Chen & Singh, 2025; Ramaila, 2024).

Simulations can also expand the kinds of phenomena to which students gain meaningful epistemic access. Quantum mechanics, electromagnetism beyond simple circuits, and statistical mechanics have historically been difficult to teach because the relevant phenomena resist direct observation. Simulations allow learners to manipulate parameters such as wavefunction characteristics or magnetic field strength and to see consequences in real time, supporting what physics-education researchers have called "epistemic exploration" of model behaviour. At the higher-education level, Villaruel (2025) reported that PhET simulations were associated with significant achievement gains among college students learning selected topics in mechanics and waves, again with effects mediated by the inquiry structure surrounding the simulation.

3.1.2 Virtual Laboratories

Virtual laboratories (VLs) extend the possibilities of simulations by replicating, in detail, the procedural and instrumental aspects of an experimental setting in a fully online or hybrid environment. VLs allow students to manipulate equipment, set up apparatus, collect data, and analyze results through high-fidelity graphical interfaces. They typically offer a closer analogue to a physical lab than do simulations, including procedural protocols, error analysis tools, and the possibility of unsafe or expensive experiments performed without physical risk.

Evidence from university physics, chemistry, and biology courses indicates that VLs can produce learning outcomes comparable to traditional laboratories while reducing costs and increasing scalability (Putri et al., 2025; Li & Liang, 2024). n university physics education, online laboratory experiences during the COVID-19 pandemic were also found to support students' self-efficacy and understanding of thermal concepts, highlighting the value of virtual labs when face-to-face experimentation is limited (Stylos et al., 2023). For schools in remote or under-resourced regions, VLs provide access to experiments that might otherwise be impossible because of safety concerns, equipment shortages, or limited teacher expertise (Shambare & Jita, 2025). Putri et al. (2025) developed an interactive mobile 3D virtual laboratory for learning ear anatomy and reported substantial gains in spatial understanding and student satisfaction, illustrating how high-fidelity VLs can support content areas such as anatomy and microbiology that are notoriously difficult to teach in conventional school laboratories.

A particularly important development concerns the integration of VLs with inquiry-based science teaching. Recent work has shown that structuring an entire inquiry cycle—question framing, hypothesis generation, experimental design, data collection, and interpretation—within a virtual environment can yield measurable improvements in learners' inquiry skills and conceptual understanding. Kolil and Achuthan (2024), in a study of chemistry students, found that incorporating VLs into inquiry-based sequences reduced the prevalence of alternative conceptions and increased awareness of laboratory practices, with gains in both procedural and conceptual outcomes. Comparable findings in physics show that flippedclassroom structures, in which VLs anchor the inquiry phase before face-to-face discussion, support both achievement and motivation more than traditional sequences (Pang et al., 2025).

The 2024 PLOS ONE meta-analysis by Li and Liang, focusing on engineering education but drawing on physics-adjacent disciplines, included 46 studies extracted from 22 publications and reported a clear advantage of VLs over traditional laboratory instruction. The authors emphasized that the size of this advantage depended on contextual factors, including discipline, level of study, and whether VLs replaced or supplemented physical experimentation. A broader bibliometric analysis of 218 articles published between 2013 and 2023 confirmed that virtual labs have demonstrated adaptability across various scientific disciplines, and identified comparisons with physical labs, student performance, and equity as the three most prominent themes in the field (Pang et al., 2025).

Adoption of VLs is mediated by factors beyond simple efficacy. Teachers' perceptions of ease of use, the availability of technical support, and alignment with assessment practices all shape uptake. Without sufficient professional development and institutional support, teachers may hesitate to incorporate VLs despite recognizing their pedagogical value (Shambare & Jita, 2025). Some teachers worry that VLs displace the development of psychomotor and instrumental skills that traditional laboratories cultivate. Recent research suggests that hybrid models, in which VLs prepare students for selected hands-on activities, extend experiments after class, or replicate experiments otherwise inaccessible, may offer a more pedagogically defensible compromise than either purely virtual or purely physical approaches. VLs should therefore not be framed as universal replacements for hands-on laboratory work. Their strongest role is to broaden access, reduce risk, support repeated practice, visualize invisible processes, and prepare students for more meaningful engagement with physical experimentation when available.

3.1.3 Augmented and Virtual Reality

Augmented reality (AR) and virtual reality (VR) represent a newer frontier in science education. These immersive technologies enable learners to "enter" molecular structures, planetary systems, or microscopic environments, creating embodied experiences that can enhance spatial reasoning and conceptual change. In AR, digital information is overlaid on the physical environment through tablets, smartphones, or head-mounted displays; in VR, students are immersed in a fully digital environment via a headset; and in mixed reality (MR), real and virtual elements interact in real time (Tene, Bonilla García, et al., 2024).

A controlled trial of AR-based physics activities with secondary students found that AR significantly improved understanding of three-dimensional electric field representations compared with textbook diagrams, particularly for learners who struggled with two-dimensional abstractions (Arici & Yilmaz, 2023). Other studies report increased motivation and collaboration when students use VR headsets to explore astronomical phenomena, virtually visit particle accelerators, or conduct virtual dissections (Kersting et al., 2024). In a 2024 systematic review of immersive educational technologies in medical and radiation physics, Tene, Bonilla García et al. analyzed 37 studies meeting strict inclusion criteria and reported consistent positive effects on engagement, performance, and the development of three-dimensional reasoning, while flagging implementation challenges related to cost, content quality, and instructor preparation.

A complementary 2024 systematic review of AR, VR, and MR in STEM identified a marked increase in research activity, with a substantial concentration of studies appearing between 2020 and 2023, partly in response to the pandemic-driven push toward digital learning (Tene et al., 2024). Across STEM, immersive technologies appear to support engagement, motivation, and certain forms of spatial reasoning, particularly when aligned with clear learning goals and supported by teacher-guided reflection. However, available evidence remains limited regarding long-term retention, transfer of learning, and cost-effectiveness at scale. Fernández-Batanero et al. (2022) showed that AR can be deliberately designed for inclusion, supporting students with intellectual disabilities to engage with abstract physics topics such as the structure of matter.

Despite these promising results, AR/VR implementations face distinctive barriers. They often require substantial hardware investment; raise questions about motion sickness, accessibility, and visual fatigue; and demand sophisticated content creation pipelines beyond the capabilities of individual teachers. Teachers must also develop new classroom-management strategies to integrate immersive experiences without fragmenting attention or overloading cognitive resources (Arici & Yilmaz, 2023; Kersting et al., 2024). The cost-effectiveness of large-scale immersive deployments remains an open question, and recent reviews note a sharp need for longitudinal studies linking immersive interventions to durable learning outcomes (Tene, Bonilla García, et al., 2024). Accessibility should therefore be treated as a design requirement rather than an optional add-on. Immersive environments may benefit learners who need concrete, visual, or spatial representations of abstract scientific phenomena, but they may also create barriers for students with visual impairments, hearing difficulties, motor limitations, vestibular sensitivity, attention difficulties, or cognitive overload. Inclusive AR/VR design should provide alternatives such as captions, audio descriptions, adjustable movement settings, non-headset modes, and teacher-controlled pacing.

3.1.4 Mobile Measurement Tools and Cross-cutting Practices

A fourth, cross-cutting development concerns the use of mobile devices—smartphones and tablets—as portable scientific instruments. Modern smartphones contain accelerometers, gyroscopes, magnetometers, barometers, light sensors, microphones, and high-quality cameras, all of which can be used to perform quantitative experiments in mechanics, acoustics, optics, electromagnetism, and even atmospheric science (Kuhn & Vogt, 2022). Free or low-cost applications such as phyphox have made these capabilities accessible at scale, allowing students to investigate phenomena such as pendulum motion, sound propagation, free fall, and the magnetic field of nearby devices without specialized laboratory equipment.

A tri-national survey of university physics laboratory instructors in Germany, Finland, and Croatia by Lahme et al. (2023) reported widespread use of smartphones and tablets for data collection, image and video analysis, and collaborative problem solving in undergraduate physics laboratories. Instructors continued to value traditional objectives such as the development of experimental skills and an understanding of measurement uncertainty, but increasingly emphasized digital competencies—particularly the ability to collect and analyze data with digital instruments—as legitimate learning outcomes in their own right. The authors noted that the COVID-19 pandemic accelerated this transition by forcing instructors to redesign their courses around technologies that students already had at home.

From a pedagogical perspective, mobile devices and tablet-based learning tools are especially valuable because they can connect classroom science with students' everyday environments. In primary physics education, one-to-one iPad use has been shown to support the teaching of abstract concepts such as energy by enabling interactive, student-centered learning activities (Kotsis & Tsiouri, 2023). When students use smartphones to record motion, sound, light intensity, magnetic fields, or atmospheric variables, they engage in practices that resemble authentic scientific inquiry: formulating investigable questions, collecting real-time data, evaluating measurement uncertainty, identifying patterns, constructing models, and using evidence to support explanations. Mobile devices also support inquiry-based field activities, in which students collect data outside the classroom and pool results through shared platforms. A 2025 scoping review of mobile learning in science education identified consistent improvements in higher-order thinking and communication skills when mobile devices were embedded in inquiry cycles that included data collection, peer comparison, and structured explanation (Pang et al., 2025). These findings reinforce a wider observation: digital tools tend to produce their largest effects not when used in isolation but when integrated into pedagogical sequences that mirror authentic scientific practices.

Across these four categories, a recurring theme is the interplay between technological affordances and pedagogical design. The technologies reviewed here do not serve identical pedagogical purposes. Interactive simulations are particularly useful when students need to visualize abstract or invisible phenomena, manipulate variables, and test conceptual relationships in real time. Virtual laboratories are most valuable when the learning goal involves procedural experimentation, repeated practice, preparation for physical lab work, or access to experiments that are costly, dangerous, or unavailable locally. AR and VR environments are especially appropriate when spatial reasoning, embodied exploration, or three-dimensional representation is central to understanding. Mobile measurement tools are most useful when teachers aim to connect science learning with everyday environments through authentic data collection, sensor-based measurement, and field inquiry.

This comparison suggests that digital technology integration should begin with the learning goal rather than the tool itself. If the objective is conceptual change, a guided simulation may be more appropriate than an immersive environment. If the objective is experimental design or procedural familiarity, a virtual laboratory may be more suitable. If the objective is spatial understanding, AR or VR may offer distinctive advantages. If the objective is authentic measurement and evidence-based reasoning, smartphones and mobile sensors may provide the strongest connection between school science and lived experience. The pedagogical value of digital technologies lies not in their novelty but in the alignment between tool affordances, scientific content, student needs, and instructional design. However, these benefits do not emerge automatically from access to digital tools. They depend on teachers' capacity to select appropriate technologies, design meaningful inquiry tasks, scaffold students' reasoning, and connect digital representations with disciplinary concepts. The next section therefore turns from the affordances of digital tools to the professional knowledge and institutional support required for their effective use.

Table 1. Synthesis of major non-AI digital technologies in science education

Technology	Main pedagogical affordances	Common science education uses	Key limitations	Conditions for effective implementation
Interactive simulations	Visualization of abstract or invisible phenomena; manipulation of variables; immediate feedback; support for prediction and testing	Physics simulations of motion, electricity, waves, fields, and quantum phenomena; chemistry simulations of molecular interactions and equilibrium; biology simulations of systems and processes	Risk of superficial exploration if students are unguided; possible disconnection from formal concepts; limited development of hands-on experimental skills	Guided inquiry tasks; prediction-observation-explanation activities; teacher questioning; structured worksheets; links to formal scientific models
Virtual laboratories	Procedural experimentation in digital environments; repeated practice; safe access to dangerous, costly, or unavailable experiments; support for data analysis	Online or hybrid experiments in physics, chemistry, biology, engineering, and laboratory preparation	May not fully develop psychomotor lab skills; depends on hardware, connectivity, and platform quality; possible over-reliance on predefined procedures	Use as complement to physical labs; pre-lab preparation; inquiry-based design; reflection on measurement, uncertainty, and experimental limitations
AR/VR and immersive environments	Spatial visualization; embodied exploration; increased engagement; representation of microscopic, astronomical, or three-dimensional systems	Molecular structures, anatomy, astronomy, electric and magnetic fields, virtual field trips, procedural training	Hardware cost; motion sickness; accessibility barriers; cognitive overload; limited long-term evidence	Inclusive design; teacher-controlled pacing; clear learning goals; alternatives for students unable to use headsets; integration with discussion and reflection

Technology	Main pedagogical affordances	Common science education uses	Key limitations	Conditions for effective implementation
Mobile measurement tools	Real-time data collection; connection between classroom science and everyday phenomena; low-cost experimentation; support for authentic inquiry	Smartphone-based experiments involving motion, sound, light, magnetic fields, pressure, video analysis, and field data collection	Variation in device quality; sensor calibration issues; data reliability; unequal student access to devices	Explicit attention to measurement uncertainty; calibration activities; collaborative data analysis; use in inquiry cycles; equitable device access
Collaborative cloud platforms	Shared data, co-authoring, peer feedback, remote collaboration, and documentation of inquiry processes	Group laboratory reports, shared datasets, collaborative modelling, online discussion, and teacher feedback	Privacy risks; platform dependency; unequal connectivity; possible distraction or superficial participation	Clear data-governance rules; structured collaboration roles; alignment with assessment; use of privacy-compliant platforms

3.2 Teacher Professional Development for Digital Integration

The successful implementation of digital technologies in science education depends not only on the availability of hardware and software but also on the knowledge, beliefs, attitudes, readiness, and practices of teachers. In the context of educational robotics, recent work has emphasized both the need for valid instruments to assess teachers' attitudes, knowledge, and application of robotics and the importance of teacher readiness for effective integration in primary and preschool education (Gavrilas & Kotsis, 2024; Gavrilas et al., 2026). Numerous studies emphasize that teachers' professional development (PD) is the single most critical factor influencing the adoption and sustained use of interactive simulations, virtual laboratories, immersive environments, and mobile measurement tools (Ertmer & Ottenbreit-Leftwich, 2010; Lahme et al., 2023). Even when infrastructure is adequate, teachers who lack confidence in their technological or pedagogical skills often underutilize digital tools or restrict their use to low-level tasks such as displaying multimedia content or projecting static diagrams during lectures.

The dominant conceptual framework for understanding teacher knowledge in this domain is Technological Pedagogical Content Knowledge (TPACK), originally developed by Mishra and Koehler and refined in subsequent work (Koehler, Mishra, & Cain, 2013). TPACK situates technology integration not as a separate competence but as the intersection of technology, pedagogy, and content—what teachers need to know in order to teach particular topics with particular tools to particular learners. Two decades after the framework's introduction, a substantial body of recent research continues to confirm its explanatory power for science teachers' digital practices (Malusay et al., 2025; Çam & Koç, 2024). Several recent studies argue that effective TPACK development requires explicit attention to subject-specific representations and instructional moves, not merely generic technology training (Kgosi et al., 2026; Wahono et al., 2025).

Effective professional development should be understood as sustained professional learning rather than short-term technical training. While teachers need practical familiarity with specific tools, meaningful integration also requires opportunities to examine pedagogical strategies, align digital activities with curriculum objectives, anticipate student misconceptions, and reflect on classroom implementation. A multi-country PD program involving secondary physics teachers demonstrated that workshops combining hands-on exploration of PhET simulations with collaborative lesson design significantly increased teachers' self-efficacy and the frequency of simulation use in classrooms (Banda & Nzabahimana, 2021). Similar outcomes have been reported in professional learning communities where teachers co-develop inquiry-based laboratory activities using virtual labs and then share classroom implementation experiences (Shambare & Jita, 2025). These collaborative models foster teacher agency and support the development of TPACK in ways that isolated, tool-focused workshops rarely achieve.

Recent evidence on online and blended PD models suggests that well-designed online programs can be as effective as face-to-face training when they incorporate active learning, modelling, sustained interaction, and authentic application tasks. The DECODE online STEM PD program, evaluated by Wahono and colleagues (2025), reported significant increases in participating teachers' understanding and ability to apply TPACK after multi-week online workshops. Çam and Koç (2024), working with teacher educators, found that a sustained PD program improved both technical and pedagogical components of TPACK and prompted participants to reconsider their role as models for the next generation of teachers. Pre-service teacher studies indicate that collaborative lesson planning activities, in which student teachers co-design ICT-enriched lessons, significantly enhance the technology-related dimensions of TPACK (Backfisch et al., 2024).

Longitudinal evidence indicates that sustained PD, rather than one-off workshops, is necessary for meaningful change. A long-term Greek project on TPACK-guided PD for mathematics and science teachers, spanning 18 years, documented how a sequence of seminars evolved into school-based collaborative design teams and ultimately into a community of practice oriented around technology-enhanced inquiry (Meletiou-Mavrotheris & Paparistodemou, 2024). The authors noted that durable change emerged only when PD shifted from generic workshops toward embedded, classroom-based co-design supported by skilled facilitators. Similarly, European university physics instructors reported that institutional support structures, such as dedicated instructional designers and technical staff, were essential for maintaining digital practices adopted during the COVID-19 pandemic (Lahme et al., 2023).

Despite these promising models, significant barriers persist. Teachers frequently cite limited preparation time, competing curricular demands, and lack of technical support as obstacles to adopting advanced digital tools (Chen & Singh, 2025). In many contexts, PD remains optional or unevenly distributed, exacerbating existing inequities. However, barriers to adoption are not only technical or organizational; they are also epistemological and pedagogical. Teachers' beliefs about what counts as authentic experimentation, valid evidence, and meaningful inquiry strongly influence how digital tools are used in practice. Teachers who view simulations or virtual laboratories primarily as substitutes for physical experiments may use them only for demonstration or confirmation, whereas teachers who view them as tools for modelling, prediction, and evidence-based reasoning are more likely to integrate them into inquiry-oriented sequences. In a study of physics teachers in Mozambique, Govender and Brás (2025) showed that even when teachers had access to simulations, their beliefs about the purpose of laboratory work strongly mediated whether they used the tools for genuine inquiry or merely as substitutes for confirmatory demonstrations. PD should therefore explicitly address teachers' beliefs about experimentation, representation, modelling, and the epistemic role of digital tools (Ertmer & Ottenbreit-Leftwich, 2010).

A further consideration concerns the diversity of teacher preparation pathways across national contexts. In high-income countries with well-resourced teacher education systems, PD is often integrated with university-based partnerships and accredited continuing professional development. In other contexts, particularly in parts of the Global South, formal pre-service preparation may include little or no exposure to digital pedagogy, and most upskilling occurs through ad hoc workshops or peer learning. Recent work argues that open educational resources (OERs) and open educational practices (OEPs) can play a strategic role in such contexts, both by reducing the cost of high-quality materials and by encouraging teachers to adapt resources to local languages and curricula (Kgosi et al., 2026; Madhav & Leibowitz, 2024). When combined with TPACK-informed scaffolding, open resources have been associated with gains in pre-service teachers' confidence and readiness to teach in digitally mediated classrooms. Taken together, the evidence suggests that effective PD for digital integration in science education should be continuous, collaborative, embedded in authentic teaching contexts, and explicitly oriented to subject-matter content. Programs that combine technical skill-building with pedagogical reflection, peer support, and authentic classroom trials are most likely to produce sustained and meaningful use of digital technologies. Such approaches also create pathways for future integration of emerging technologies, including artificial intelligence, by cultivating a culture of experimentation and reflective practice (Oktaviani & Utami, 2024).

3.3 Ethical and Policy Considerations

Teacher professional development is necessary for meaningful digital integration, but it is not sufficient on its own. Even well-prepared teachers operate within broader institutional, technological, legal, and economic systems that shape what tools are available, how they are used, and who benefits from them. While the pedagogical benefits of interactive simulations, virtual laboratories, and immersive digital environments are increasingly well documented, their widespread adoption raises ethical and policy concerns that must be addressed to ensure equitable and responsible implementation. These concerns intersect across at least five dimensions: equity and the digital divide; data privacy and the protection of minors; intellectual property and open access; the environmental footprint of digital systems; and the broader governance of platform-mediated education. Each is now considered in turn.

3.3.1 Equity and the Digital Divide

Persistent inequalities in infrastructure remain one of the most pressing challenges. Access to high-speed internet, up-to-date hardware, and reliable electricity varies dramatically across and within countries, creating what UNESCO has called a "digital learning gap" (UNESCO, 2023). As of 2024, approximately 2.6 billion people worldwide—32% of the global population—still lacked internet access, with 1.8 billion living in rural areas (UNESCO, 2025). In education specifically, around 60% of primary schools, half of lower secondary schools, and a third of upper secondary schools globally were not connected to the internet (UNESCO, 2025). Rural schools and low-income urban districts are particularly vulnerable, as students in these settings may lack both school-based resources and home connectivity (Rajasekaran et al., 2024).

Without targeted policies and funding, the expansion of digital technologies risks exacerbating existing educational inequities rather than reducing them. Gottschalk and Weise's (2023) working paper on digital equity emphasizes that ensuring access is necessary but not sufficient: meaningful digital inclusion requires designing tools, professional development, and curricula around the needs of marginalized learners from the outset rather than as an afterthought. This perspective aligns with the Rewired Global Declaration on Connectivity for Education, jointly issued by UNESCO and partners, which calls on policymakers to "centre the most marginalised" in their digital strategies (UNESCO, 2023). Research in sub-Saharan Africa illustrates the practical consequences: even when virtual laboratories are freely available online, inconsistent bandwidth and hardware shortages limit their use (Shambare & Jita, 2025). In several documented cases, rural schools possess the hardware needed to run lightweight simulations but lack the connectivity required for asynchronous video, large data sets, or cloud-based collaboration. International initiatives such as the ITU–UNICEF Giga programme, which has mapped over 800,000 schools across 30 countries and works to mobilize blended public–private funding for connectivity, attempt to address this gap, but progress remains uneven (UNICEF/ITU).

Equity considerations extend beyond physical access. Even when students nominally have internet access, differences in device quality, bandwidth reliability, quiet study space, parental digital literacy, language support, and prior experience with digital tools can produce substantial inequalities in educational value (Gottschalk & Weise, 2023; Lohr, 2025). In science education, these inequalities are especially important because digital tools often require students to manipulate representations, interpret data, collaborate online, or navigate complex interfaces. Designing for equity therefore requires attention to the full ecology of digital learning, not merely to the presence of a device. This includes accessible interfaces, multilingual resources, offline or low-bandwidth options, teacher support, and classroom routines that ensure all students can participate meaningfully in inquiry-based activities.

3.3.2 Data Privacy and the Protection of Minors

Many digital science education tools require student accounts or collect usage data to track learning progress. These data can be valuable for formative assessment, but they also raise serious concerns about privacy, consent, and potential commercial exploitation. In the European Union and the United Kingdom, the General Data Protection Regulation (GDPR) imposes stringent requirements on the processing of children's personal data, including special rules on consent, data minimization, and the use of sub-processors. Studies of educational technology providers' privacy policies have highlighted persistent gaps between school-level practices and the formal requirements of the GDPR, particularly in relation to third-party educational apps (Jarke & Breiter, 2019; Barud et al., 2024). A 2024 analysis of EdTech vendors' data protection policies found significant variation in clarity and completeness of disclosures, and concluded that many policies fall short of the standards required to enable informed school-level decision making.

In the United States, the regulatory landscape is fragmented: the Family Educational Rights and Privacy Act (FERPA) governs the institutional handling of education records, the Children's Online Privacy Protection Act (COPPA) imposes requirements on services directed at children under 13, and individual states have enacted their own student data privacy laws (UNICEF, 2024). The result is a multi-layered compliance environment in which a single EdTech platform may need to satisfy GDPR, FERPA, COPPA, and one or more state laws simultaneously. Practitioners increasingly emphasize that compliance cannot be reduced to checklists; rather, it requires governance structures, vendor oversight, and ongoing monitoring of data flows (UNICEF, 2024).

Recent data breaches underscore the stakes involved. The education sector has become an increasingly attractive target for cyberattacks because schools and educational platforms often process large amounts of sensitive personal information, including student identities, assessment data, attendance records, and sometimes health or family information. High-profile incidents involving educational technology providers demonstrate that privacy risks are not merely hypothetical but can directly affect students, families, teachers, and school systems. Teachers and administrators often lack the technical expertise to evaluate whether digital tools comply with privacy standards. The challenge is particularly acute for science education tools that integrate with broader school information systems, since the boundaries between learning analytics, performance data, and personally identifiable information are often blurred.

A complicating factor concerns the validity of consent in school settings. Under the GDPR, consent must be freely given, but in educational contexts where particular platforms are mandated by the school or required to participate in lessons, students and parents may have no real choice to refuse (UNICEF, 2024). Regulatory authorities therefore increasingly emphasize that consent may not be the appropriate legal basis for processing children's data in schools, and that public-interest or contractual bases should be considered instead. From a practical standpoint, science teachers selecting a virtual lab or simulation platform should consider not only its pedagogical features but also its data protection architecture, including the location of data storage, the role of sub-processors, and the mechanisms for data subject rights.

3.3.3 Intellectual Property and Open Access

Another policy issue concerns intellectual property rights over digital learning materials. Open-source simulation platforms such as PhET, which operate under permissive Creative Commons licenses, provide free access and remixing rights that have made them especially valuable for under-resourced contexts (Banda & Nzabahimana, 2021). By contrast, many commercial virtual laboratory products operate under proprietary models that can create long-term financial dependencies for schools and limit teachers' ability to adapt materials to local curricula or languages. Policymakers must balance the need to incentivize innovation with the imperative to keep essential educational resources affordable and adaptable.

In the Global South in particular, OERs and open educational practices have emerged as a strategic response to structural inequities in access to textbooks, laboratories, and up-to-date STEM content (Kgosi et al., 2026; Madhav & Leibowitz, 2024). Recent debates around OERs in STEM education have also highlighted tensions around quality assurance, sustainability of OER infrastructure, and the recognition of contributions to open materials in academic career structures. Although these issues fall outside immediate classroom decision-making, they shape the long-term availability of high-quality, freely usable resources and therefore have important implications for educational equity.

3.3.4 Sustainability and Environmental Impact

Although often overlooked in pedagogical discussions, the environmental costs of digital technologies have become part of the ethical landscape of educational technology. Data centres supporting cloud services, the energy consumption of large language models and streaming video, the manufacture and disposal of hardware, and the carbon embedded in network infrastructures all contribute to the sector's overall footprint. Critical analyses argue that the rapid expansion of digital platforms in education must be evaluated not only for pedagogical benefits but also for alignment with climate targets such as those set out in the Paris Agreement (Taylor & Vai, 2026; Shengjergji et al., 2024).

UNESCO's 2024 Digital Learning Week placed particular emphasis on the alignment of digital transformation with environmental sustainability, exploring how to measure and mitigate the carbon footprint of educational platforms (UNESCO, 2025). Recent reports from independent organizations call for the integration of sustainability criteria into EdTech procurement, the adoption of renewable energy for cloud services, and the development of eco-friendly content (Shengjergji et al., 2024). At the level of teacher education, an emerging body of research examines the digital carbon footprint awareness of pre-service teachers, finding that explicit instruction in "digital sobriety" can shift attitudes and reported behaviour around online practices. Sustainable procurement policies, equipment recycling programmes, and cloud services powered by renewable energy are emerging as important considerations for education ministries and school districts. For science educators specifically, this opens an opportunity to align curriculum and practice: lessons about climate change, energy efficiency, or the life cycle of materials can be enacted not only as content but also as a reflection on the school's own digital infrastructure.

3.3.5 Platform Governance and Commercial Influence

Beyond the four axes above, a fifth concern has come to the fore: the governance of educational platforms operated by large technology companies. Critical scholars argue that the expansion of platform-based education risks creating long-term dependencies in which schools, ministries, and even research communities become locked into ecosystems controlled by a small number of commercial actors (Taylor & Vai, 2026). For science education specifically, the question is whether decisions about pedagogy, assessment, and learning analytics increasingly reflect the design choices of platforms rather than the considered judgement of educators and curriculum experts. These concerns are not abstract. As simulations, virtual labs, and immersive environments are increasingly delivered through commercial platforms—often as part of broader productivity or learning management suites—decisions about data formats, interoperability, accessibility, and content moderation acquire educational consequences. Policymakers have responded with frameworks emphasizing transparency, vendor accountability, and the right of schools and learners to data portability (Gottschalk & Weise, 2023; UNICEF, 2024). Ensuring that science teachers retain meaningful agency over the tools they use will be one of the defining policy challenges of the coming decade.

At the school and system level, responsible digital integration requires more than the purchase of devices or software licences. Institutions should adopt clear criteria for selecting digital science tools, including pedagogical relevance, accessibility, data protection, interoperability, teacher usability, long-term cost, and environmental sustainability. Schools and universities should also maintain inventories of approved tools, provide guidance on privacy-compliant use, and ensure that teachers receive both technical and pedagogical support before new platforms are introduced. At the policy level, ministries and education authorities should prioritize open standards, public or open educational resources where appropriate, transparent procurement processes, and funding models that prevent digital innovation from widening existing inequalities. Addressing all of these issues requires coordinated action at multiple levels. Governments must invest in infrastructure to reduce the digital divide, establish clear data privacy regulations, support PD so that educators can make informed choices about technology adoption, and integrate sustainability criteria into procurement. International organizations such as UNESCO and the OECD have begun to provide policy frameworks, but local adaptation and community engagement remain critical for equitable implementation.

3.4 Implications for Research and Practice

The findings of this review suggest several implications for future research, classroom practice, teacher education, and policy. For research, there is a need for more longitudinal studies that examine retention, transfer, and the sustained use of digital technologies beyond short intervention periods. Future studies should move beyond simple comparisons between digital and traditional instruction and instead examine how specific design features, scaffolding strategies, teacher interventions, and assessment practices mediate learning outcomes. Particular attention should be given to under-represented contexts, including rural schools, low-resource settings, multilingual classrooms, and learners with disabilities.

For classroom practice, the evidence suggests that digital tools should be used to support inquiry, modelling, explanation, and evidence-based reasoning rather than as decorative additions to instruction. Teachers should begin by identifying the scientific concept, skill, or inquiry practice they want students to develop and then select the digital tool that best supports that goal. Interactive simulations are particularly appropriate for helping students visualize invisible phenomena, manipulate variables, and test conceptual relationships. Virtual laboratories are most useful when students need procedural practice, repeated experimentation, or access to experiments that are unsafe, expensive, or unavailable in the local school context. AR and VR environments are most appropriate when spatial reasoning, embodied exploration, or three-dimensional representation is central. Mobile measurement tools are especially valuable when teachers want students to collect authentic data from everyday environments. In all cases, digital activities should include prediction, observation, data interpretation, discussion, and reflection so that students connect digital representations with formal scientific concepts.

For teacher education and PD, digital competence should be developed as part of subject-specific pedagogical expertise. Pre-service and in-service programs should provide teachers with opportunities to design, test, revise, and evaluate digital science lessons in authentic classroom contexts. Such programs should address not only technical skills but also teachers' beliefs about experimentation, modelling, inquiry, and the epistemic role of digital representations in science learning. For policy, the review highlights the need for coordinated investment in infrastructure, open and accessible resources, privacy-compliant platforms, and sustainability-oriented procurement. Digital transformation in science education should be evaluated not only by the number of devices or platforms adopted but by the extent to which these technologies improve equitable access to meaningful scientific inquiry.

4. CONCLUSION

This review shows that interactive simulations, virtual laboratories, immersive digital environments, and mobile measurement tools can enrich science education when integrated through purposeful pedagogical design. Across the reviewed literature, these technologies appear most valuable when they help students visualize invisible phenomena, manipulate variables, engage in inquiry, collect and interpret data, and connect scientific models with observable or simulated evidence. Their educational value, however, is not inherent in the tools themselves. It depends on instructional guidance, curriculum alignment, infrastructure, and teachers' capacity to use technology in ways that support scientific reasoning rather than simply digitize traditional instruction.

Effective digital integration requires sustained teacher professional development. Teachers need more than technical familiarity with platforms; they need opportunities to design, test, evaluate, and revise digital science lessons in authentic classroom contexts. TPACK-informed professional learning, collaborative lesson design, and communities of practice are especially important because they connect digital tools with subject-specific pedagogy, inquiry-based learning, and students' conceptual difficulties.

At the same time, digital transformation in science education raises ethical and policy challenges that cannot be addressed at classroom level alone. Inequalities in access to devices and connectivity, concerns about student data privacy, dependence on proprietary platforms, and the environmental footprint of digital systems require coordinated institutional and policy responses. Responsible digital integration therefore requires investment not only in hardware and software, but also in open resources, accessible design, privacy-compliant platforms, sustainable procurement, and equitable support for schools and teachers.

The review also has implications for the emerging era of AI-enhanced science education. The lessons learned from non-AI digital technologies remain directly relevant: new tools will not automatically improve learning unless they are supported by sound pedagogy, teacher expertise, inclusive infrastructure, and ethical governance. AI-driven systems may extend the possibilities of digital science learning, but they may also reproduce or intensify existing inequalities if introduced without these foundations. In conclusion, digital technologies should be understood not as stand-alone solutions but as pedagogical resources embedded in broader educational systems. Their promise lies in their capacity to expand access to scientific representations, experimentation, inquiry, and data analysis. This promise will be realized only when technological innovation, teacher professional learning, equity, privacy, and sustainability advance together.

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