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TECHNOLOGY-ENHANCED SCIENCE TEACHING FOR 21ST-CENTURY LEARNING: A SYSTEMATIC REVIEW OF EVIDENCE-BASED STRATEGIES AND THEIR ALIGNMENT WITH SDG 4

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ABSTRACT

The evolving demands of 21st-century education require science teaching strategies that promote student engagement, critical thinking, and real-world application. Although many studies examine individual approaches, consolidated evidence identifying which strategies best align with modern educational outcomes—and what large-scale evidence from the fully online COVID-19 period implies—remains limited. This study systematically reviews and synthesizes high-quality empirical evidence on technology-enhanced strategies for teaching science, with a focus on their use in teacher education programs. Guided by the PICO framework, a comprehensive search across seven major databases (2015–2025) yielded 133,414 records. After applying predefined inclusion/exclusion criteria and conducting critical appraisal using the JBI checklists and ROBVIS, 23 studies met eligibility for analysis. Thematic synthesis revealed three dominant categories of effective strategies: (1) immersive technologies (e.g., augmented reality, virtual reality, interactive simulations); (2) collaborative digital platforms (e.g., Google Classroom, Edmodo, Internet Reciprocal Teaching); and (3) interactive learning tools (e.g., virtual laboratories, gamified slide presentations, digital flipbooks). Across diverse disciplines and grade levels, these strategies generally improved engagement, conceptual understanding, and scientific literacy under controlled or well-supported conditions. Triangulation with evidence from fully online learning during COVID-19, however, indicates heterogeneous—and at scale, often negative—system-level outcomes when enabling conditions are weak, as reflected in international assessments (e.g., PISA 2022). Distinct from prior reviews, this study integrates technology-enhanced pedagogy with SDG 4 goals, providing a global synthesis that bridges instructional innovation and sustainable education frameworks. The findings underscore the importance of professional development, curriculum alignment, and equitable technology access as enabling conditions for successful implementation. We conclude that student-centered, technology-enhanced approaches embedded within inquiry- or project-based frameworks can advance learning outcomes while supporting quality, inclusive, and future-ready science education.

Keywords: 21st-century education; science teaching strategies; flipped classroom; inquiry-based learning; teacher professional development

INTRODUCTION

Science education plays a pivotal role in achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 4: Quality Education, which calls for inclusive, equitable, and high-quality learning opportunities for all. Equipping learners with 21st-century competencies—such as critical thinking, creativity, collaboration, problem-solving, and digital literacy—is essential to building sustainable societies and preparing future generations to address complex global challenges (UNESCO, 2022). Yet, in many education systems, traditional didactic approa-

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ches remain dominant, limiting opportunities for active engagement, conceptual understanding, and real-world application of scientific knowledge (Haryani et al., 2021).

In such contexts, science lessons are frequently delivered through lecture-based instruction that emphasizes rote memorization, formula recall, and textbook-driven content coverage, with few opportunities for hands-on experiments, inquiry-based tasks, or collaborative problem-solving. These teacher-centered approaches restrict student-centered exploration and constrain learners' ability to develop higher-order thinking skills or to apply concepts meaningfully to authentic scientific and societal issues.

System-level evidence from the COVID-19 period, when schooling shifted fully online for extended durations, paints a troubling picture. International assessments such as PISA and national monitoring across several countries report achievement declines and reduced engagement in STEM—particularly among secondary-level learners in low- and middle-income contexts (OECD, 2023). This evidence contrasts with small-scale studies in science education that demonstrate promising outcomes for ICT-assisted strategies under well-supported conditions. The tension between micro-level promise and macro-level outcomes highlights a critical research gap: which technology-enhanced strategies remain effective beyond classroom-bound trials, and under what enabling conditions can they be scaled equitably and sustainably?

In this review, evidence-based science learning refers to instructional practices grounded in systematically collected empirical data—such as quasi-experimental studies, randomized controlled trials, and mixed-methods designs—that demonstrate measurable improvements in student outcomes. These outcomes typically include conceptual understanding, scientific literacy, problem-solving, and engagement. Unlike traditional methods that rely on intuition or convention, evidence-based approaches are validated through peer-reviewed research and replicated across contexts. By prioritizing such practices, schools and teacher education programs can adopt strategies that consistently enhance learning rather than relying on untested innovations or anecdotal successes.

Previous studies have often examined single strategies in isolation, such as flipped classrooms (Pangandaman, 2018; Pangandaman, Mukattil, Lambayong, et al., 2024), inquiry-based instruction (Abaniel, 2021), gamification (Pangandaman et al., 2025), and project-based learning (Alali, 2024). While these approaches have reported gains in engagement, conceptual understanding, and scientific literacy, integrative syntheses that compare effects across contexts and explicitly align findings with sustainability goals remain limited (O'Flaherty & Liddy, 2018; Carrión-Martínez et al., 2020). A review of the literature in internationally reputable journals shows that most prior studies either concentrate on a single strategy or lack explicit connections to global sustainability agendas such as the SDGs (Kioupi & Voulvoulis, 2019; Rashid, 2019; Amorós Molina et al., 2023).

Systematic reviews in this field are scarce and often restricted to particular regions, subject areas, or technologies, without synthesizing findings into a broader framework for teacher education and professional development. This gap limits the ability of policymakers, educators, and curriculum developers to make informed decisions about scaling effective, sustainable practices (Imara & Altinay, 2021; Fischer et al., 2022; Quintana-Ordorika et al., 2024).

To address this gap, the present study systematically reviews high-quality empirical research on effective, technology-enhanced teaching strategies for science in the 21st century, explicitly linking these strategies to the goals of quality, inclusive, and future-ready education. This study aims to support and extend previous research by consolidating evidence from multiple contexts and technologies, while also identifying enabling conditions for successful implementation. The novelty of this work lies in its dual contribution: (1) synthesizing diverse, evidence-based science teaching strategies into an SDG-aligned framework, (2) providing actionable insights for integrating these strategies into teacher education and professional development programs worldwide, and (3) sharing bright and dark sides of using online learning in relation to the context of the study.

The urgency of this research lies in the widening gap between rapid technological innovations in education and the inconsistent learning outcomes observed globally during and after the pandemic. While small-scale classroom studies report encouraging effects of technology-enhanced strategies, large-scale assessments such as PISA 2022 reveal alarming declines in achievement and engagement, especially in STEM fields. This mismatch underscores the need to identify strategies that are not only evidence-based but also scalable, sustainable, and equitable. Aligning these innovations with SDG 4 (Quality Education) adds to the urgency, as education systems worldwide must recover from learning loss, reduce inequities, and equip students with the competencies necessary to tackle complex global challenges.

METHODS

This study employed a systematic review methodology consistent with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines, with adaptations to address the study objectives and alignment with the Sustainable Development Goals (SDGs). The process was organized into six sequential stages.

Stage 1 – Defining the Research Question. The review was guided by the PICO framework—Participants, Intervention, Comparison, and Outcomes—to formulate the central question: "What are the most effective technology-enhanced instructional strategies for improving student engagement and scientific literacy in secondary school science classrooms?" This ensured that the scope of the review remained clear, focused, and measurable.

Table 1 outlines the PICO framework applied in this study, clarifying that the review focuses on science educators and students (Participants), evaluates modern evidence-based strategies such as flipped classrooms and inquiry-based learning (Intervention) against traditional lecture methods (Comparison), and measures their impact on teaching effectiveness, student engagement, academic performance, and scientific literacy (Outcomes).

By identifying science educators and students as the primary participants, the study highlights both instructional delivery and learner outcomes. The interventions—flipped classrooms, inquiry-based instruction, and project-based learning—represent student-centered strategies that integrate technology to foster active engagement. Traditional lecture-based methods serve as the baseline for comparison, enabling assessment of the added value of these modern pedagogies.

The defined outcomes—teaching effectiveness, student engagement, academic performance, and scientific literacy—offer clear performance indicators that align with the objectives of 21st-century education and SDG 4: Quality Education. This structured framework ensures that all included studies are directly relevant to the research purpose, thereby facilitating a focused and coherent synthesis of evidence.

Table 1. Description of PICO

People/ Participants	**Faculty members and students involved in science education.**
Intervention	Modern, evidence-based teaching strategies such as flipped classrooms, inquiry-based instruction, and project-based learning.
Comparison	Traditional lecture-based teaching methods vs technology integration (ICT-assisted online learning) during and after pandemic period (COVID-19).
Outcomes	Improved teaching effectiveness, student engagement, academic performance, and science competency.

Stage 2 – Literature Search Strategy. A comprehensive search was conducted across seven international databases—ScienceDirect, Scopus, ProQuest, EBSCOhost, Sage Journals, Taylor & Francis, and PubMed—covering publications from January 2015 to May 2025. Boolean operators (AND, OR), phrase searching, and parentheses grouping were applied to combine search terms related to teaching strategies, technology integration, and science education (e.g., "flipped classroom" AND "science teaching" AND "21st-century"). The search strategy was adapted from similar systematic reviews (e.g., Pangandaman et al., 2024; Liu et al., 2023) but modified to include SDG-related keywords.

Stage 3 – Eligibility Criteria. Studies were included if they:

1. Focused on science teaching strategies in secondary education or teacher education programs.
2. Involved technology-enhanced or student-centered pedagogies.
3. Reported measurable outcomes in engagement, literacy, or performance.
4. They were empirical, peer-reviewed, and published in English between 2015 and 2025.

Exclusion criteria comprised theoretical articles, protocols, non-science education studies, inaccessible full texts, and those with insufficient methodological detail.

Stage 4 – Screening and Selection. Records retrieved were imported into Mendeley Reference Manager for duplicate removal. Two independent reviewers screened titles, abstracts, and then full texts against the eligibility criteria. Disagreements were resolved through discussion or consultation with a third reviewer. The process was documented in a PRISMA 2020 flow diagram to ensure transparency (see Figure 1).

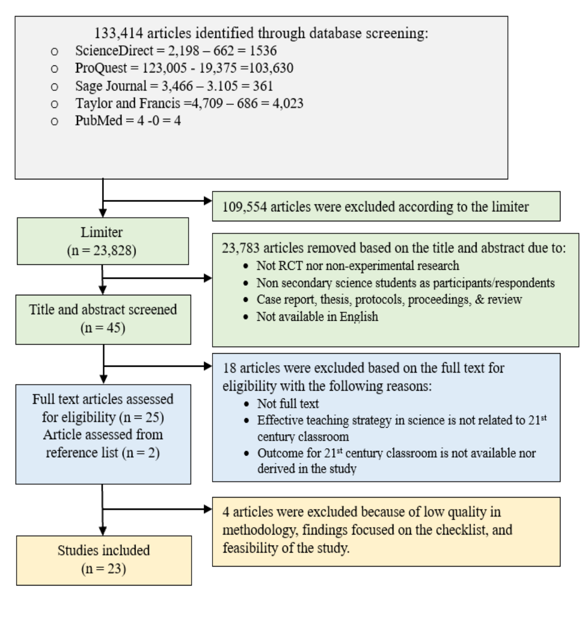

Figure 1. PRISMA Flowchart

Stage 5 – Data Extraction. A standardized data extraction template—adapted from JBI's systematic review toolkits—was used to record: author, year, country, study design, participants, intervention details, duration, outcomes, and key findings. The template was piloted on three randomly selected studies to ensure clarity and reliability before full extraction.

Stage 6 – Quality Appraisal and Risk of Bias Assessment. The Joanna Briggs Institute (JBI) Critical Appraisal Checklists were applied to quasi-experimental studies, while the ROBVIS tool was used for randomized controlled trials. Modifications to these tools included the addition of SDG-relevance criteria (e.g., alignment with SDG 4 targets). Studies scoring ≥70% on JBI criteria or with low risk of bias in ROBVIS were classified as high quality. To assess methodological quality, the Joanna Briggs Institute (JBI) Critical Appraisal Checklists were applied to all quasi-experimental studies. This tool evaluates nine methodological domains, including clarity of cause and effect, similarity of participants, consistency in treatment, and reliability of measurement. Table 2 presents the results of this risk of bias assessment, indicating the percentage of "Yes" responses for each criterion and the corresponding interpretation of bias risk levels.

Table 2. Risk of Bias Assessment for Quasi Experiment Design

Author & Year	JBI Assessment Tools										Interpretation[b]
	Q1[a]	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	% Yes	
Lavonen et al. (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Leelamma & Indira (2017)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Suwono et al. (2021)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Demelash et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Iskandar et al. (2019)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Hartomo & Sukmawati (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Rosa et al. (2023)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Tabbu et al. (2023)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias

Mafarja et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Ogunjobi & Owoseni (2025)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Zhumash & Zhumagulova (2025)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Priadi et al. (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Meng & Jumaat (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Ananayo (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Riska et al. (2023)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Laili et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Kruit et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias
Velarde-Camaqui et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	100	Low risk of bias

Notes:
[a] Q1 – Q9 indicate questions 1 to 9 based on the JBI risk assessment
[b] The risk of bias was ranked as high when the study reached up to 49% of "yes" scores, moderate when the study reached from 50 to 69% of "yes" scores, and low when the study reached more than 70% of "yes" scores
[c] Not means "Unclear"

For randomized controlled trials (RCTs), the ROBVIS tool was employed to visualize and assess risk of bias across six domains: allocation concealment, blinding, incomplete outcome data, selective reporting, other biases, and overall bias. Table 3 summarizes the assessment outcomes, using symbols to denote low (+), high (-), and unclear (?) risk of bias for each domain.

Table 3. ROBVIS Risk of Bias Tool for RCT

Author (s) & year	Sample size (n)	Allocation concealment	Blinding	Incomplete outcome data	Selective reporting	Other bias	Overall
Shamsudin & Talib (2023)	60	+	?	+	?	+	?
Wang & Tse (2024)	45	+	+	+	+	+	+
Note: (+) indicates a low risk of bias, (-) indicates a high risk of bias, (?) shows unclear risk of bias							

Given the methodological heterogeneity, a Synthesis Without Meta-analysis (SWiM) approach was adopted (Campbell et al., 2020). Studies were grouped into thematic categories—immersive technologies, collaborative digital platforms, and interactive learning tools—based on intervention type. Patterns of effectiveness were interpreted in relation to educational theory, contextual factors, and SDG alignment.

As shown in Table 2, all quasi-experimental studies achieved 100% "Yes" scores across the nine JBI criteria, signifying a consistently low risk of bias. This high methodological quality suggests strong internal validity, which enhances confidence in the reported intervention effects. The uniformity of high scores across studies reflects rigorous study designs, standardized implementation, and reliable outcome measures.

As indicated in Table 3, the RCTs generally demonstrated low risk of bias across most domains, with minor areas of unclear bias primarily due to incomplete reporting on blinding procedures. These findings support the reliability of the RCT evidence while highlighting the need for more detailed methodological reporting in future studies

RESULTS AND DISCUSSION

Figure 1 presents the PRISMA 2020 flow of study selection. From 133,414 records identified across ScienceDirect, Scopus, ProQuest, EBSCOhost, Sage Journals, Taylor & Francis, and PubMed (January 2015–May 2025), 109,554 were removed during de-duplication and basic eligibility checks (peer-reviewed, English language, science education relevance, SDG 4 alignment). Title and abstract screening excluded 23,818 records, leaving 27 full texts for assessment. Of these, four were excluded after JBI and ROBVIS appraisal, resulting in 23 high-quality articles included in the synthesis.

To reduce potential bias from an overreliance on short, small-scale interventions, this review explicitly contrasts micro-level findings with large-scale evidence generated during the fully online COVID-19 period. In particular, international assessments and national monitoring documented system-level learning deficits and widening disparities during the pandemic. Most notably, PISA 2022 reported unprecedented average declines in mathematics and reading across OECD countries compared to 2018 (with uneven patterns in science), while meta-analytic evidence indicated persistent learning deficits of about 0.14 SD across 15 countries, even 2.5 years into the pandemic.This systematic review synthesized findings from the 23 high-quality empirical studies into three primary categories of strategies: immersive technologies, collaborative digital platforms, and interactive learning tools. Each category demonstrated distinct strengths in fostering student engagement, conceptual understanding, and scientific literacy, providing valuable insights for strengthening science instruction in 21st-century classrooms. These insights were also interpreted within the context of the COVID-19 shift to online learning, where digital methods became the predominant mode of instruction.

Table 4 summarizes the characteristics of the included studies, detailing country of origin, educational level, subject focus, technology type, pedagogical model, and main outcomes. The diversity of contexts—from Indonesia and the Philippines to Malaysia and beyond—demonstrates the broad applicability of these teaching strategies. Variation across subject domains (physics, biology, chemistry, environmental science, agricultural science, and STEM literacy) and research designs (quasi-experimental, randomized controlled trials, and mixed methods) enriches the synthesis by enabling cross-comparative insights. This heterogeneity strengthens the external validity of the findings, as the interventions were tested across diverse socio-cultural and educational settings. Mapping these details provides a foundation for the thematic categorization that follows.

Table 4. Characteristics of Included Studies

Study (Author/year)	Study Design	Technology Type	Grade Level	Subject Area
(Wen et al., 2020)	Pre-test/post-test, mixed methods	Interactive simulation with embedded inquiry support	8th grade	Science
(Lavonen et al., 2023)	Quasi-experimental	Digital tools in project-based learning	Upper secondary	Physics (Newtonian mechanics)
(Leelamma & Indira, 2017)	Quasi-experimental, pre-test/post-test	Mobile-assisted inquiry-based learning environment	Secondary	Environmental science
(Suwono et al., 2023)	Quasi-experimental, pre-test/post-test	Digital platform for socio-scientific inquiry	10th grade	Biology
(Demelash et al., 2024)	Quasi-experimental, mixed methods	Simulation-integrated 7E instructional model (context-based)	10th grade	Chemistry
(Iskandar et al., 2019)	Quasi-experimental, pre-test/post-test	Edmodo-assisted inquiry	10th grade	Physics
(Hartomo & Sukmawati, 2024)	Quasi-experimental, pre-test/post-test	Digital flipbook in project-based learning	Grade V	Science (digestive system)

(Shamsudin & Talib, 2023)	Randomized controlled trial, pre-test/post-test, mixed methods	Augmented reality (three-dimensional models)	Secondary	Science
(Putri et al., 2021)	Pre-test/post-test	Virtual laboratory with inquiry	8th grade	Physics (light/optics)
(Kruit et al., 2025)	Quasi-experimental	Web-based instrument for socio-scientific issues	Secondary	Science/argumentation
(Rosa et al., 2023)	Quasi-experimental, pre-test/post-test	Guided inquiry via Google Classroom	11th grade	Biology
(Tabbu et al., 2023)	Quasi-experimental	Virtual reality-assisted smart teaching	11th grade	Environmental science (climate)
(Mafarja et al., 2024)	Quasi-experimental, pre-test/post-test	Cooperative learning with Internet reciprocal teaching	12th grade	Physics (STEM literacy)
(Ogunjobi & Owoseni, 2025)	Quasi-experimental, pre-test/post-test	Technology-enhanced instruction	Senior secondary	Agricultural science
(Zhumash & Zhumagulova, 2025)	Quasi-experimental, pre-test/post-test	Computer programs and video films	Secondary	Biology
(Priadi et al., 2022)6}	Quasi-experimental, pre-test/post-test	Online discovery learning via Google Classroom	10th grade	Science (ecosystems)
(Meng & Jumaat, 2024)	Quasi-experimental, pre-test/post-test	Online inquiry-based learning	Secondary	Science
(Ananayo, 2024)	Quasi-experimental, pre-test/post-test, mixed methods	ClassPoint in PowerPoint	8th grade	Science
(Riska et al., 2023)	Quasi-experimental	Guided inquiry with virtual laboratory	10th grade	Physics (momentum/impulse)
(laili et al., 2024)	Quasi-experimental, pre-test/post-test	Project-based learning with Moodle web	Junior high	Science/technology literacy
(Wang & Tse, 2025)	Randomized controlled trial, pre-test/post-test	Interactive simulations	8th grade	Physics
(Takda et al., 2024)	Pre-test/post-test	Digital flipbook (Flip PDF Professional) in Inquiry-based Science Instructional Tool	Junior high	Science
(Velarde-Camaqui et al., 2024)	Mixed methods, quasi-experimental, longitudinal	Augmented reality instructional design	High school	Biology

Immersive technologies—including augmented reality (AR), virtual reality (VR), and interactive simulations—bring abstract scientific phenomena to life by enabling tangible, multimodal, and embodied interaction. These tools allow learners to engage with complex processes such as molecular dynamics, planetary motion, or ecosystem feedbacks in ways that narrow the gap between conceptual models and lived experiences. In doing so, they align with dual-coding theory and the cognitive theory of multimedia learning, which emphasize the benefits of combining visual and verbal modes of representation.

For instance, AR applications enable students to project 3D models of the human circulatory system onto their classroom desks, allowing them to "walk through" blood vessels and observe how oxygen is transported. Similarly, VR headsets can immerse learners inside a cell, where they explore organelles as if navigating a physical environment, thereby reinforcing cellular biology concepts. Interactive simulations, such as virtual physics labs, allow students to manipulate variables like force, velocity, or resistance in a controlled digital space, giving them opportunities to practice experimental design without the constraints of a physical laboratory. Collectively, these applications illustrate how immersive technologies extend beyond visualization to active exploration, making science lessons more engaging and cognitively accessible.

Despite their promise, implementing AR and VR in classrooms presents significant challenges. High equipment costs and uneven access to reliable internet infrastructure hinder equitable adoption, particularly in under-resourced schools. Teachers often face steep learning curves in mastering the technical and pedagogical integration of immersive platforms, which can result in inconsistent use. Prolonged use of head-mounted displays may also cause discomfort or motion sickness for some learners, raising issues of accessibility and inclusivity. Moreover, time constraints, curriculum alignment, and the lack of localized content complicate efforts to scale these tools beyond pilot programs. These barriers underscore the need for systemic support, including teacher training, infrastructure investment, and robust instructional design.

Across classroom-level studies, AR/VR consistently demonstrates sizeable gains in engagement, conceptual understanding, and science literacy, particularly when embedded within inquiry-oriented pedagogies. For example, AR-based lessons report large effects on engagement and literacy (Shamsudin & Talib, 2023) , VR-supported environmental science modules strengthen both conceptual grasp and pro-environmental dispositions (Zhang & Wang, 2021), and AR-infused activities enhance digital literacy and data interpretation skills (Brown et al., 2021). These benefits are most reliable when immersive tools are positioned as means to enact pedagogical intentions—such as hypothesis testing, model revision, and evidence-based argumentation—rather than treated as ends in themselves.

However, evidence from large-scale implementations during the COVID-19 fully online period tempers expectations of generalizability. International assessments reported unprecedented system-level declines in mathematics and reading, with uneven patterns in science, compared to pre-pandemic baselines. Meta-analyses further documented persistent learning deficits of approximately 0.14 SD across 15 countries, even 2.5 years into the recovery period. These population-level findings suggest that the strengths observed in short-duration, small-scale AR/VR interventions do not automatically extend to long-term, large-scale contexts without enabling conditions. Unequal device and connectivity access, variability in teacher digital-pedagogical readiness, and limited opportunities for guided inquiry in remote settings all diminish or negate potential benefits.

In this review, the studies that integrated AR/VR within structured, student-centered pedagogies—such as project-based, problem-based, or guided inquiry—reported more durable learning gains than those treating immersion as a novelty (Quintero et al., 2019; Nesenbergs et al., 2021). This aligns with broader evidence showing that the quality of instructional design outweighs technological novelty in predicting outcomes (Park et al., 2024). Effective designs explicitly highlighted the epistemic practices of science (e.g., modeling, explanation, and argument from evidence), scaffolded cognitive load, and connected virtual experiences to hands-on or data-rich tasks.

The findings also underscore enabling conditions often overlooked in prior reviews, including equitable device access, comprehensive teacher training in both technical and pedagogical domains, and alignment with curriculum goals (Pangandaman et al., 2019; Akram et al., 2022; González-Pérez & Ramírez-Montoya, 2022). The novelty of this synthesis lies in reframing immersive technologies not merely as visual enhancements but as pedagogically grounded and context-sensitive tools for sustained science learning.

The scale and duration comparator applied in this review further clarifies boundary conditions. In short-term, small-scale studies (e.g., single classes or schools lasting ≤ one term), AR/VR often improves proximal outcomes such as interest, time-on-task, and near-transfer conceptual tests. In contrast, triangulation with long-term, large-scale evidence from the pandemic period indicates that, without robust infrastructure, sustained professional development, and assessments valuing inquiry processes, system-level achievement gains are inconsistent and equity gaps may widen.

In sum, immersive technologies remain a powerful lever for conceptually rich, engaging science learning. Yet their scalability depends on context: reliable hardware and connectivity, teacher capacity to orchestrate inquiry with AR/VR, and school-level routines that integrate immersive tasks with assessment and feedback. Where these enabling conditions are in place, the classroom-level advantages documented in this synthesis are more likely to persist over time and contribute to SDG 4–aligned improvements in science education at scale.

Collaborative platforms such as Google Classroom, Edmodo, and structured approaches like Internet Reciprocal Teaching provide virtual spaces for dialogue, feedback, and shared artifact creation. When embedded in explicit pedagogical scripts, these tools can translate social interaction into disciplinary understanding. In the classroom-level studies included in this review, platform-mediated inquiry and collaboration were associated with substantial gains in science literacy, participation, and reasoning quality when teachers established clear roles, aligned tasks with curriculum goals, and linked online exchanges to data-rich or hands-on activities (Pinto & Leite, 2020; Kapur et al., 2022). For example, integrating Google Classroom with guided-inquiry lessons yielded a 49.9% improvement in literacy scores alongside higher levels of critical questioning and participation (Rosa et al., 2023), while Internet Reciprocal Teaching promoted collaborative meaning-making and reflective thinking that enhanced STEM literacy (Mafarja et al., 2024). These findings align with social-constructivist accounts of learning, where understanding is co-constructed through interaction and scaffolded problem solving.

Earlier research often examined platforms in isolation, focusing on usability or generic engagement metrics rather than pedagogy (Acosta-Gonzaga & Ramirez-Arellano, 2022; Iskandar et al., 2019; Wang & Tse, 2025). By contrast, the studies synthesized here indicate that the platform itself is not the causal engine. Instead, measurable learning gains emerge when platforms are integrated into well-designed instructional frameworks—such as guided inquiry, cooperative learning, or flipped classrooms—that specify epistemic moves like modeling, explanation, and argumentation from evidence (Pinto & Leite, 2020; Kapur et al., 2022).

Triangulation with large-scale evidence from the fully online COVID-19 period further clarifies boundary conditions for impact. Despite near-universal adoption of LMSs and communication tools during school closures, international and national monitors reported declines in achievement and widening disparities relative to pre-pandemic baselines, indicating that access to platforms alone was insufficient to sustain learning at scale (OECD, 2023). In Indonesia, ministry reports and independent analyses similarly documented pandemic-era learning loss, prompting system-level responses such as Kurikulum Merdeka (Kartika et al., 2023; Sumilat & Mochtar, 2024). Interpreted through our scale/period comparator, short-term, small-scale classroom studies often reported positive outcomes because teachers enforced accountable-talk norms, provided timely feedback, and aligned online discourse with graded scientific practices. In contrast, long-term, large-scale implementations during the pandemic frequently devolved into upload-and-submit routines characterized by feedback delays, uneven task quality, and participation gaps tied to device and connectivity access.

At the same time, the open and interactive nature of collaborative platforms introduces the risk of distraction, particularly when learners use personal devices with competing notifications, social media, or unrelated browsing. Even within structured activities, students may deviate from task goals, resulting in fragmented attention and reduced depth of engagement. Several studies highlight that without strong teacher facilitation, digital accountability measures, and well-structured prompts, platform use may inadvertently encourage surface-level participation rather than sustained inquiry (Swart et al., 2022).

Nevertheless, the literature identifies enabling conditions that sustain learning even in large-scale contexts: coherent weekly problem cycles, explicit metacognitive prompts, synchronous sense-making to complement asynchronous discussion, and assessment rubrics that reward evidence-based explanation rather than mere task completion. Complementary capacity-building—such as professional development in digital pedagogy, standardized lesson structures across teaching teams, and equitable access initiatives—also emerges as critical for translating platform interactions into durable conceptual understanding (Trenerry et al., 2021; Swart et al., 2022; Abdulkhaled & Pangandaman, 2025). Taken together, these findings position collaborative platforms as amplifiers of pedagogy within SDG-aligned, equity-conscious ecosystems. Where instructional design and enabling conditions are robust, the classroom-level gains observed in this review are more likely to persist beyond the short term and to scale effectively.

Interactive learning tools—such as gamified slide presentations, digital flipbooks, and virtual laboratories—are designed to promote active processing through manipulable representations, immediate feedback, and adaptive content delivery. By allowing learners to vary parameters, test hypotheses, and visualize dynamic processes, these tools support higher-order thinking and deeper conceptual understanding, consistent with multimedia learning and dual-coding principles. In the classroom-level studies included in this review, their effects were strongest when tools were embedded within structured pedagogies rather than used as stand-alone novelties. For example, virtual laboratories integrated into the 7E model produced substantial engagement gains that translated into measurable improvements in science literacy (Demelash et al., 2024). Digital flipbooks embedded in project-based sequences enhanced conceptual retention, self-paced learning, and motivation (Hartomo & Sukmawati, 2024). Gamified slide presentations, when aligned with inquiry-driven designs, improved participation and attitudes toward learning (Gündüz & Akkoyunlu, 2020; Mukattil & Pangandaman, 2024; Pangandaman et al., 2025).

Several studies caution, however, that such gains may be inflated by the novelty effect—a temporary boost in motivation and engagement when learners are exposed to unfamiliar or entertaining digital formats. While initial excitement can raise participation and short-term test scores, it does not always translate into durable conceptual understanding or knowledge transfer. Without sustained scaffolding, repeated exposure, and alignment with curricular goals, interactive tools risk losing their motivational appeal over time, leading to diminishing returns. This underscores the importance of distinguishing between engagement driven by novelty and learning outcomes anchored in pedagogical design.

Juxtaposing these short-term, small-scale successes with large-scale evidence from the fully online COVID-19 period further clarifies expectations. During 2020–2022, international assessments recorded unprecedented average declines in mathematics and reading relative to 2018 (with uneven patterns in science), despite near-ubiquitous reliance on digital tools and platforms. A multi-country meta-analysis likewise found persistent learning deficits of ≈0.14 SD more than two years into the pandemic. These population-level results suggest that the benefits observed in well-scaffolded, tool-rich lessons do not automatically generalize to long-duration, large-scale implementations without enabling conditions in place.

National monitoring supports this interpretation. In Indonesia, for example, World Bank analyses and ministry-affiliated reports documented pandemic-era learning losses and motivated recovery initiatives such as Kurikulum Merdeka, underscoring that infrastructure, teacher capacity, and assessment alignment mediate whether interactive tools can sustain learning at scale.

Viewed through the scale/period comparator, patterns are consistent. In single-class or single-school studies lasting a term or less, virtual labs and other interactive tools reliably boosted proximal outcomes—time-on-task, engagement, and near-transfer conceptual tests—because teachers could closely coach inquiry moves, sequence cognitive demand, and tie digital tasks to graded scientific practices. By contrast, during long-period, large-scale implementations in the pandemic, tool use often devolved into assignment-submission routines marked by delayed feedback, uneven task quality, and participation gaps linked to device and connectivity constraints. These factors blunted the conceptual advantages of interactivity at the population level. This pattern echoes earlier critiques that overestimated the sufficiency of interactivity without attending to retention, transfer, or scalability (Sukackė et al., 2022; Guaña-Moya et al., 2024) and supports evidence that instructional design quality outweighs technological novelty in predicting learning outcomes (Ní Chróinín et al., 2018; Susanto et al., 2020).

Accordingly, this synthesis emphasizes enabling conditions for effectiveness and scalability: close alignment of tools with curriculum; teacher professional development that integrates content, pedagogy, and technology; and scaffolds that manage cognitive load while structuring collaborative sense-making. Where such conditions were present, interactive tools functioned as components of pedagogy-driven ecosystems rather than as add-ons, producing more durable gains (Darling-Hammond et al., 2020; Pangandaman, Mukattil, Salve, et al., 2024; Tene et al., 2024). In short, interactive tools are powerful levers for conceptually rich science learning, but their impact at scale depends on context—especially equitable access, teacher orchestration of inquiry, and assessment practices that value explanation and evidence. When these conditions are met, the classroom-level advantages documented across the included studies are more likely to persist beyond the short term and contribute to SDG 4–aligned improvements in science education.

To integrate findings across categories, this review proposes a conceptual framework for technology-enhanced science education. The model illustrates how immersive technologies, collaborative digital platforms, and interactive learning tools can be combined within pedagogy-driven ecosystems. Immersive technologies provide multisensory representations that make abstract concepts tangible; collaborative platforms foster peer dialogue, feedback, and co-construction of meaning; and interactive tools support inquiry, experimentation, and adaptive practice. When strategically orchestrated, these categories reinforce each other—for instance, an AR simulation (immersive) embedded in Google Classroom (collaborative) with a virtual lab follow-up (interactive) can create a cycle of visualization, discussion, and experimentation. The framework further emphasizes enabling conditions—teacher professional development, curriculum alignment, equity of access, and assessment reform—as the foundational supports that determine whether integration leads to sustained learning gains.

To ensure that technology-enhanced science strategies scale equitably and sustainably, ministries of education should embed them into national curricula through structured inquiry models, while teacher training institutions must strengthen preservice and in-service programs in digital pedagogy. At the same time, investments in infrastructure to close device and connectivity gaps, coupled with assessment reforms that reward explanation and evidence over rote completion, are essential for aligning classroom innovations with long-term system goals under SDG 4.

CONCLUSION

This systematic review synthesized evidence from 23 high-quality empirical studies to identify technology-enhanced strategies that consistently support 21st-century science learning. Three clusters—immersive technologies, collaborative digital platforms, and interactive learning tools—demonstrated clear strengths in promoting engagement, scientific literacy, conceptual understanding, and motivation when embedded within well-designed, student-centered pedagogies and supported by teacher professional development, curriculum alignment, and equitable access. Crucially, triangulating classroom-level findings with large-scale evidence from the COVID-19 period, when schooling shifted fully online, reveals important boundary conditions. International assessments and national monitoring documented system-level learning deficits during the pandemic, with particularly pronounced declines in mathematics and reading and uneven patterns in science. These results demonstrate that the positive effects observed in short-term, small-scale interventions do not automatically generalize to long-term, large-scale implementations. This underscores a central insight: technology is an amplifier of pedagogy and capacity. Without robust infrastructure, teacher readiness in digital pedagogy, and assessment practices that reward explanation and evidence use, the adoption of platforms and tools alone is insufficient to sustain learning at scale. Taken together, our findings point to an SDG 4–aligned integrative framework: immersive tools make abstract phenomena tractable; collaborative platforms organize dialogic sense-making; and interactive tools structure inquiry and feedback. Their effectiveness, however, depends on being situated within coherent instructional designs and supported by equitable enabling conditions. For policy and practice, the implication is clear: investments should prioritize teacher development, curriculum-technology coherence, connectivity and device access, and routines that link digital activity to formative assessment. For research, future syntheses and trials should report outcomes by scale and period (including fully online and hybrid contexts) and track longer-term retention and transfer to determine which designs remain effective and equitable beyond the short term. In this way, technology-enhanced science education can move beyond promising pockets of practice toward resilient, system-level gains that advance the goals of quality, inclusion, and equity articulated in SDG 4.

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