

 Review Article

Transforming Science Education: A Systematic Review of Evidence-Based Strategies for Cultivating 21st-Century Skills in STEM Education

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Abstract

The accelerating demands of the 21st century require science education to evolve beyond traditional content delivery and to cultivate skills such as critical thinking, collaboration, digital literacy, and global awareness. This systematic review examines 20 empirical studies published between 2017 and 2025 to identify evidence-based instructional strategies, namely inquiry-based learning, project-based learning, and integrated STEM approaches and immersive technologies (virtual reality, augmented reality, and simulations) that support the development of these competencies. Studies were retrieved from ScienceDirect (Scopus) and Google Scholar, screened against predefined inclusion and exclusion criteria, and synthesised through thematic analysis. Findings demonstrate that scaffolded inquiry and project-based frameworks consistently enhance critical thinking, creativity, and collaboration, particularly when complemented by structured reflection and visual-tool support. Immersive technologies amplify engagement and conceptual understanding, especially when metacognitive prompts accompany virtual or hands-on laboratory experiences. Integrated-STEM and EthnoVLab models further underscore the value of interdisciplinary, context-rich projects for motivation and higher-order skill acquisition. Equity-centred designs that incorporate assistive technologies and professional development for teachers are shown to be vital for inclusive implementation. Persistent barriers include limited access to technology, insufficient teacher training, and uneven policy support. The review highlights the need for longitudinal, mixed-method, and comparative investigations to assess the durability of 21st-century skill gains and to refine discipline-specific assessment tools. Implications extend to researchers, who should pursue innovative study designs; to policymakers, who must embed interdisciplinary, equity-focused standards and support structures; and to practitioners, who can pilot blended-STEM initiatives with peer-learning networks. Ultimately, this work offers actionable insights for bridging traditional pedagogy and contemporary educational demands, fostering sustainable reforms in science education.

Keywords: Collaboration, Critical Thinking, Digital Literacy, Inquiry-Based Learning, STEM Education

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1. INTRODUCTION

In the rapidly evolving landscape of the 21st century, science education faces unprecedented challenges and opportunities. Technological advancements and the increasing complexity of global issues (Baz et al., 2022; Hassan et al., 2022; Wolff, 2021) necessitate a transformation in educational approaches to adequately prepare students for future demands (Singha & Singha, 2024). Traditional teaching methods, which often emphasise rote memorisation and passive learning, are increasingly viewed as insufficient for developing the critical thinking and problem-solving skills essential in today's world (Carter et al., 2016; Ojo & Tijani, 2025; Tijani, 2025; Persky et al., 2018). As a result, educators and policymakers have a growing

consensus on integrating 21st-century skills into science curricula to enhance student engagement and learning outcomes.

The concept of 21st-century skills encompasses a broad set of competencies, including critical thinking, communication, collaboration, and digital literacy. According to Ojo (2017) and Pellegrino (2014), these skills are essential for students to navigate the complexities of modern society and the workforce. In science education, fostering these competencies involves shifting from teacher-centred instruction to more interactive and student-centred learning environments. Such a transformation encourages students to actively engage in scientific inquiry, develop problem-solving abilities, and apply their knowledge to real-world situations.

Implementing this shift requires the adoption of innovative instructional strategies that promote active learning and critical engagement with scientific concepts. Inquiry-based learning, for instance, encourages students to explore scientific questions through hands-on experiments and collaborative research (Kapici et al., 2022; Kotsis, 2024; Saad, 2020). Beyond fostering critical thinking and collaboration, robust science instruction has been shown to drive employment generation and GDP growth in Nigeria (Tijani & Adeduyigbe, 2025). Similarly, project-based learning allows students to work on complex problems over extended periods, fostering deeper understanding and skill development (Aksela & Haatainen, 2019; Anazifa & Djukri, 2017). Integrating technology into the classroom further supports these approaches by providing access to digital tools and resources that enhance learning experiences (Ojo, 2017; Wang & Li, 2022). In particular, immersive technologies such as VR-based virtual labs and AR-enhanced models provide interactive, hands-on experiences that deepen students' conceptual understanding and engagement (Ibáñez & Delgado-Kloos, 2018). These tools allow students to visualise abstract concepts, conduct safe virtual experiments, and collaborate in shared virtual spaces, fostering a deeper connection between theoretical knowledge and practical applications.

Despite the clear benefits, integrating 21st-century skills into science education presents several challenges. Lawrence and Tar (2018) stated that resource limitations, such as inadequate access to technology and insufficient teacher training, can impede the effective implementation of innovative teaching strategies. Persistent gender disparities in students' conceptual understanding and engagement, especially in physics, have been documented (Adeduyigbe et al., 2025), underscoring the need for gender-responsive instructional strategies in STEM education. In addition, existing educational policies may not fully support the necessary curricular changes, leading to inconsistencies in the adoption of new teaching methods. Addressing these challenges requires a concerted effort from educators, policymakers, and communities to ensure that all students have the opportunity to develop the skills essential for success in the modern world.

Looking forward, the future of science education lies in its ability to adapt to emerging technologies and evolving societal needs. The integration of artificial intelligence, virtual reality, and other advanced technologies holds the potential to revolutionise teaching and learning processes (Kumar et al., 2023). However, realising this potential depends on the development of comprehensive policies that prioritise educational innovation and equity. By embracing these changes, science education can play a pivotal role in preparing students to meet the challenges and opportunities of the 21st century.

To address these critical needs, it is imperative to identify and implement instructional strategies that equip educators with the tools necessary for fostering 21st-century competencies. A comprehensive understanding of essential skills and effective teaching approaches will not only enhance student outcomes but also contribute to the broader goal of preparing a scientifically literate and socially responsible workforce. As a result, this study uses a systematic review to synthesise current research to provide actionable insights into how science education can be reimagined to align with the demands of a rapidly changing world. The study aims to bridge the gap between traditional educational practices and the innovative strategies required for modern classrooms. To align science education with the demands of the 21st century, this review seeks to answer the following questions:

1. What are the essential 21st-century skills and evidence-based instructional strategies needed to modernise science education?
2. How do inquiry-based learning (IBL) and project-based learning (PBL), under different scaffolding and contextual supports, enhance critical thinking, problem-solving, and student engagement in science classrooms?

3. What role do immersive technologies (e.g., VR, AR, simulations) play in fostering experiential learning, motivation, and interdisciplinary collaboration in STEM education?
4. What challenges (e.g., resource access, teacher training) hinder the integration of these skills and strategies, and how can they be addressed to promote equity and scalability?

2. LITERATURE REVIEW

2.1. STEM Education Models

STEM (Science, Technology, Engineering, and Mathematics) education models advocate for an interdisciplinary approach that integrates science, technology, engineering, and mathematics disciplines into cohesive learning experiences. Unlike traditional subject-specific teaching, STEM education focuses on real-world applications, encouraging students to apply concepts from multiple disciplines to solve complex problems (Ibáñez & Delgado-Kloos, 2018; Martín-Páez et al., 2019). These models are grounded in the belief that integrating science, technology, engineering, and mathematics better prepares students to tackle global challenges and excel in innovation-driven careers. A key feature of STEM education models is their emphasis on inquiry and problem-solving, promoting critical thinking and creativity (Ardianti et al., 2020; Manokore & Sibanda, 2024; Sari et al., 2020; Zulyusri et al., 2023). For instance, in a STEM-focused classroom, students might engage in projects such as designing renewable energy systems or developing prototypes to address local environmental issues. Such activities foster not only technical skills but also collaboration, communication, and adaptability, which are essential for the 21st-century workforce.

In the context of this study, STEM education models are highly relevant as they provide a framework for evaluating instructional strategies that support transformative learning experiences. By encouraging interdisciplinary learning, these models align with the study's aim of identifying essential skills for modern science education. Moreover, STEM education approaches are well-suited to inquiry-based and project-based learning strategies, which have been shown to enhance students' conceptual understanding and engagement (Almulla, 2020; Cairns & Areepattamannil, 2017; Ibáñez & Delgado-Kloos, 2018). Emerging technologies, including immersive tools such as VR-based simulations, AR-enhanced models, and interactive virtual labs, further expand the potential of STEM education models. These technologies promote active, hands-on learning by allowing students to manipulate 3D molecular structures, simulate chemical reactions, and interact with scientific models in real time (Ibáñez & Delgado-Kloos, 2018). Research shows that students using immersive simulations demonstrate higher engagement, improved conceptual understanding, and stronger problem-solving skills compared to those using traditional digital tools (Kumar et al., 2023).

2.2. Importance of Identifying 21st-Century Skills and Strategies for Transforming Science Education

Transforming science education to meet the demands of the 21st century requires a dual focus on the essential skills students need to develop and the instructional strategies educators should adopt to effectively teach these skills (Chu et al., 2016; Häkkinen et al., 2016; Malik, 2018; Soulé & Warrick, 2015). The interplay between these two elements is critical for achieving meaningful educational outcomes. Identifying both the skills and strategies necessary for this transformation is essential for several reasons. Identifying 21st-century skills and strategies is crucial for enhancing student engagement in science education. When students perceive learning as relevant to real-world applications, their interest and motivation significantly increase (Almulla, 2020). Strategies such as project-based learning (PBL) immerse students in authentic tasks, fostering active participation and a deeper understanding of scientific concepts (Jumaat et al., 2017). This engagement is particularly essential for bridging the gap between abstract theoretical knowledge and its practical applications in scientific inquiry.

Moreover, engaging instructional approaches encourage students to take ownership of their learning processes. For example, inquiry-based learning promotes curiosity and critical thinking by allowing students to explore scientific questions and experiments independently (Cairns & Areepattamannil, 2017). This approach transforms the classroom into a dynamic space where students actively construct knowledge rather than passively receiving information. Such strategies are integral to fostering a lifelong love for

science and learning. Ultimately, enhancing engagement through these methods contributes to better academic outcomes and personal growth. Students exposed to active learning environments are more likely to develop skills like collaboration, communication, and critical thinking, which are indispensable in modern scientific careers (Chu et al., 2016). Thus, identifying and implementing the right strategies is pivotal for creating a generation of motivated and competent scientists.

The rapid evolution of technology and globalisation demands that science education prepare students for a dynamic workforce. Identifying essential skills such as computational thinking and adaptability ensures that students are equipped to meet these challenges (Mutakinati et al., 2018). Similarly, strategies like STEM-integrated project-based learning emphasise interdisciplinary collaboration, mirroring the teamwork required in professional scientific environments (Ardianti et al., 2020).

Furthermore, modern industries require a workforce adept at solving complex problems. Teaching methods that prioritise critical thinking and problem-solving, such as inquiry-based learning, address this need by helping students analyse data and develop innovative solutions to real-world issues (Kapici et al., 2022). These approaches provide students with a competitive edge in their careers while fostering adaptability to technological advancements. Thus, the alignment of educational practices with workforce demands also supports national and global economic growth. A science-educated workforce equipped with 21st-century skills drives innovation and sustains industries reliant on technological and scientific expertise (Tytler, 2020). Thus, integrating relevant skills and strategies into science education not only benefits individual students but also contributes to broader societal progress.

Identifying and incorporating 21st-century skills and strategies are vital for promoting equity in science education. All students, regardless of background, should have access to high-quality learning experiences that prepare them for future challenges (Malik, 2018). For example, digital tools and online platforms enable equitable access to resources, reducing disparities in educational opportunities across socio-economic groups (Lawrence & Tar, 2018). Strategies like hands-on inquiry and cooperative learning further enhance inclusivity by accommodating diverse learning needs and styles. For instance, research by Adeduyigbe et al. (2024) highlights certain challenges faced by students with hearing impairments in typical educational environments and calls for revamping science education to better accommodate them. By integrating 21st-century teaching strategies, technology, and skills into the curriculum for children with disabilities, these issues can be resolved. However, it will be impossible to accomplish this if educators in the sciences are not aware of the abilities and tactics required and their significance in modernising science teaching.

Furthermore, equity-focused strategies also address systemic barriers to education. For instance, experiential learning approaches have been shown to empower underrepresented groups by fostering confidence and providing practical skills applicable to their contexts (Singha & Singha, 2024). This ensures that marginalised students are not left behind in the pursuit of academic and professional success. By promoting equity, science education can serve as a powerful tool for social mobility and inclusion. Ensuring all students have the opportunity to develop critical 21st-century skills creates a more equitable and just society while enriching the scientific community with diverse perspectives and talents (Sari et al., 2020).

Science education in the 21st century increasingly emphasises interdisciplinary collaboration, reflecting the interconnected nature of modern scientific endeavours. Identifying essential skills like teamwork and cross-disciplinary thinking prepares students to work effectively in collaborative settings (Ardianti et al., 2020). Strategies such as STEM-focused project-based learning simulate real-world scenarios, allowing students to tackle complex problems requiring knowledge from multiple domains (Ibáñez & Delgado-Kloos, 2018). Moreover, interdisciplinary approaches enhance creativity and innovation. When students integrate concepts from science, technology, engineering, and mathematics (STEM), they gain a broader perspective and develop unique solutions to challenges (Martín-Páez et al., 2019). This holistic approach mirrors professional practices, where breakthroughs often emerge from collaborative efforts across fields. Encouraging collaboration also fosters a sense of global citizenship. Students who engage in interdisciplinary projects develop the communication and cultural competency needed to address global challenges, such as climate change and public health crises (Hassan et al., 2022). As a result, science education becomes a platform for cultivating not only scientific expertise but also the collaboration skills critical to addressing pressing world issues.

The rapid pace of technological advancements necessitates fostering lifelong learning skills through science education. Identifying strategies such as inquiry-based learning helps students develop curiosity and self-directed learning habits essential for continuous skill development (Kapici et al., 2022). Lifelong learning ensures that students remain adaptable and competent in navigating evolving scientific landscapes. Incorporating 21st-century skills like critical thinking and adaptability into education equips students to independently seek knowledge and solve problems in diverse contexts (Persky et al., 2018). For example, experiential learning strategies allow students to apply theoretical knowledge in practical scenarios, reinforcing their capacity to learn from real-world experiences (Singha & Singha, 2024). These skills not only enhance academic achievement but also enable students to thrive in professional environments.

Moreover, emphasising lifelong learning in science education promotes resilience in the face of challenges. By cultivating a mindset of continuous improvement and curiosity, students can better adapt to changes in their fields and contribute to innovative solutions to complex problems (Kotsis, 2024). Thus, integrating these strategies into curricula is key to preparing students for success beyond the classroom.

In the 21st century, technology is central to science education. Identifying skills like digital literacy ensures students can effectively engage with modern tools and platforms (Wang & Li, 2022). Strategies such as augmented reality and blended learning enable educators to create immersive learning experiences that enhance conceptual understanding (Ibáñez & Delgado-Kloos, 2018). Technological integration also supports personalised learning. For instance, adaptive learning systems use data analytics to tailor instruction to individual student needs, promoting more effective and efficient learning outcomes (Häkkinen et al., 2016). This ensures that students receive support aligned with their unique learning paces and preferences. Additionally, integrating technology fosters collaboration and global connectivity. Digital platforms allow students to work on projects with peers from different regions, broadening their perspectives and enhancing their communication skills (Wolff, 2021). By embedding these skills and strategies in science education, students can be better prepared to succeed in a technology-driven world.

Creativity and innovation are at the heart of scientific progress, making it essential to identify and integrate skills and strategies that foster these attributes. Project-based learning (PBL) provides students with opportunities to explore open-ended questions and design unique solutions to problems (Anazifa & Djukri, 2017). This encourages divergent thinking and equips students with the ability to tackle complex challenges creatively. Moreover, hands-on, inquiry-based approaches stimulate creative problem-solving by immersing students in real-world scenarios where they must apply their knowledge innovatively (Saad, 2020). These strategies also build confidence, as students learn to trust their ideas and experiment with unconventional methods. Encouraging creativity in science education ultimately drives technological and scientific advancements. Students who develop innovative mindsets contribute to breakthroughs in fields such as renewable energy, biotechnology, and artificial intelligence, shaping a more sustainable and prosperous future (Baz et al., 2022). Thus, fostering creativity through effective educational strategies is vital for scientific and societal progress.

Critical thinking and problem-solving are indispensable in addressing the multifaceted challenges of the modern world. Inquiry-based teaching methods have been shown to significantly enhance these skills by engaging students in the process of questioning, hypothesising, and analysing data (Cairns & Aarepattamannil, 2017). Such strategies encourage students to think deeply and systematically about scientific concepts. Similarly, STEM-focused education that integrates real-world applications of science fosters analytical and problem-solving abilities (Ardianti et al., 2020). For instance, collaborative projects allow students to address complex problems, honing their ability to work through challenges collectively while considering multiple perspectives. The development of these skills not only benefits academic performance but also prepares students to tackle global issues like climate change, public health, and technological disruptions (Hassan et al., 2022). By embedding critical thinking and problem-solving into science education, future leaders capable of addressing pressing societal needs are cultivated.

Science education plays a crucial role in equipping students to address global challenges. Identifying skills like systems thinking and environmental awareness ensures that students can understand and address complex, interconnected issues (Martín-Páez et al., 2019). Strategies such as simulation-based inquiry learning provide realistic contexts for students to analyse global problems and test potential solutions (Sari et al., 2020). Furthermore, fostering a global perspective in science education encourages students to consider cultural and societal contexts in their problem-solving processes. For example, experiential and

inquiry-based learning models allow students to collaborate with peers worldwide, promoting intercultural understanding and cooperation (Singha & Singha, 2024). Equipping students with the skills and strategies to address global challenges positions them as proactive contributors to a sustainable future. From combating climate change to innovating in renewable energy, science education prepares the next generation to take on roles that shape a better world (Hassan et al., 2022).

The integration of 21st-century skills and strategies into science education is essential for driving educational reform. Skills like adaptability and collaboration align with the needs of a rapidly changing world, making education more relevant and impactful (Mutakinati et al., 2018). Reforming curricula to include these elements ensures that students are prepared for both academic and professional success. Innovative teaching strategies such as project-based and blended learning are at the forefront of this transformation. These approaches actively engage students in meaningful learning experiences, moving away from traditional, passive methods of instruction (Jumaat et al., 2017). This shift not only improves academic outcomes but also cultivates skills essential for lifelong learning. Educational reform rooted in 21st-century skills also addresses equity and access. By integrating technology and hands-on learning, schools can create inclusive environments that meet the diverse needs of all learners (Lawrence & Tar, 2018). These reforms are critical for ensuring that science education remains a driving force for progress in an increasingly interconnected world.

3. METHODOLOGY

This study employs a systematic literature review (SLR) to identify and synthesise research on essential 21st-century skills and instructional strategies for transforming science education. The SLR approach ensures a comprehensive, transparent, and replicable review process, facilitating the identification of trends and evidence-based practices in contemporary science education.

3.1. Inclusion and Exclusion Criteria

The review focuses on peer-reviewed articles published between 2017 and 2025. The inclusion criteria are as follows:

1. Studies that explicitly address 21st-century skills or instructional strategies in science education.
2. Research that evaluates the impact of these skills or strategies on student outcomes such as engagement, critical thinking, and problem-solving.
3. Empirical papers published in reputable academic journals and/or indexed in Scopus.
4. Empirical studies that provide data and theoretical insights.
5. Articles published as open access and freely accessible to readers from different parts of the world.

Conversely, the exclusion criteria include:

1. Studies unrelated to science education or lacking a clear focus on 21st-century skills and strategies.
2. Opinion pieces, editorials, or conceptual papers without empirical support.
3. Research focused on non-academic or non-educational contexts.
4. Non-English papers, conference proceedings, books, and review articles.
5. Papers that are not Scopus-indexed, ensuring relevance and credibility in the systematic review.

3.2. Search Procedure

A systematic search was conducted in Scopus and Google Scholar databases for English-language, peer-reviewed journal articles published between 2017 and 2025. The period from 2017 to 2025 was selected for this review to capture recent developments in science education, especially in relation to 21st-century skills and instructional strategies. This timeline reflects a transformative era marked by the global implementation of education-focused Sustainable Development Goals (SDGs), rapid advancements in educational technology, and significant shifts in teaching practices following the COVID-19 pandemic. These years witnessed increased emphasis on digital literacy, critical thinking, collaboration, and innovative pedagogies, making the selected period both timely and relevant for examining how science education is evolving to meet 21st-century demands. Titles, abstracts, and keywords were queried using the Boolean

string (“21st-century skills” OR “21st century competencies” OR “digital literacy” OR “critical thinking”) AND (“science education” OR STEM OR “instructional strategies” OR “project-based learning” OR “inquiry-based learning”). In Scopus, filters restricted results to journal articles in English, yielding 858 records; in Google Scholar, the first 200 results sorted by relevance and date range were retrieved. After removing 156 duplicates, 902 unique records were screened by title and abstract, 153 full texts were assessed for eligibility, and 20 studies met all inclusion criteria (see Figure 1 below for details).

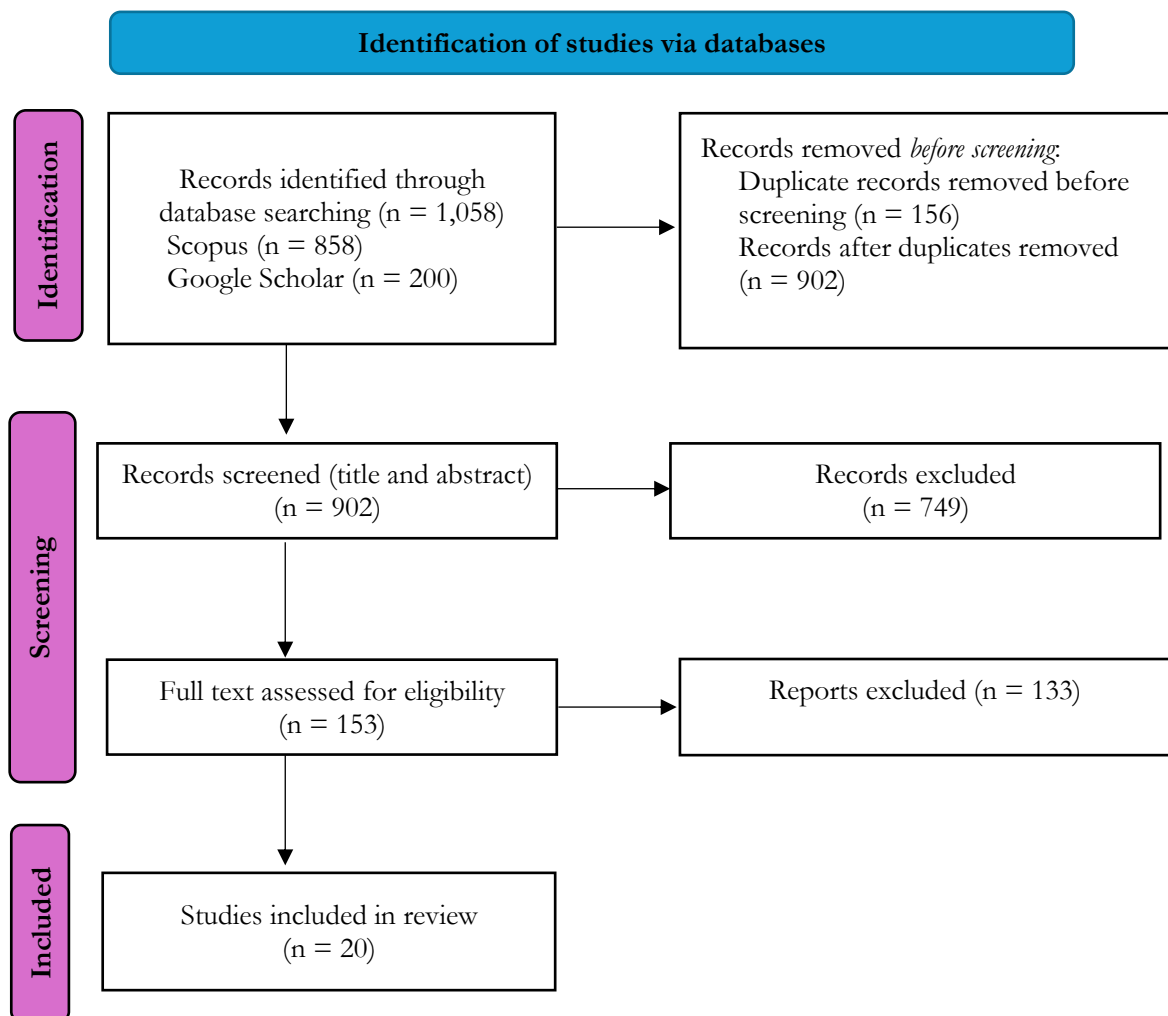


Figure 1. PRISMA Flow Diagram of the Search Procedure and Study Selection Process (based on: Page et al., 2021)

3.3. Study Selection Process

The study selection process involved three stages:

1. Title and Abstract Screening: Titles and abstracts of all retrieved articles were reviewed for relevance based on the inclusion criteria.
2. Full-Text Review: Articles meeting the initial criteria were subjected to a full-text review to confirm their suitability for inclusion.
3. Quality Assessment: Each article was assessed for methodological rigour and relevance using a pre-defined checklist that included criteria such as clarity of research objectives, robustness of methodology, and validity of findings (Critical Appraisal Skills Programme, 2023).

Following this rigorous selection process, a total of 20 studies met the inclusion criteria and were used for data analysis and synthesis. These studies provided empirical evidence on essential 21st-century

skills and instructional strategies in science education, forming the foundation for the thematic synthesis and discussion.

3.4. Mitigating Bias

To minimise bias, the two authors independently conducted the article screening and quality assessment processes. Discrepancies in the selection or assessment of studies were resolved through discussion and consensus.

3.5. Data Extraction and Analysis

Key information, such as study objectives, methodologies, key findings, and implications, was extracted using a structured data extraction form. Thematic analysis was employed to identify recurring themes and trends related to essential skills and instructional strategies in science education. Coding was conducted iteratively to refine themes and ensure comprehensive coverage.

3.6. Data Analysis and Synthesis

The data extracted from the 20 selected studies were analysed using thematic synthesis to identify recurring patterns and significant trends in science education research. A systematic coding process was employed to categorise findings based on essential 21st-century skills, instructional strategies, and their impact on student learning outcomes. Thematic analysis facilitated the identification of key themes, such as critical thinking, digital literacy, collaboration, and STEM integration, ensuring a comprehensive understanding of the literature. To enhance reliability, an inter-coder agreement was established by involving multiple reviewers in the coding and synthesis process. The synthesis of findings was guided by a comparative approach, allowing for the evaluation of similarities and differences across studies while highlighting gaps in existing research. The results of this analysis informed the discussion on evidence-based strategies for transforming science education and their implications for educators, policymakers, and researchers.

4. FINDINGS

This systematic review synthesises recent research to identify the essential 21st-century skills and evidence-based instructional strategies necessary for transforming science education. The findings emphasise the critical relationship between developing students' cognitive, digital, interpersonal, and societal skills and implementing innovative teaching approaches. These elements form the foundation for a transformative learning experience that prepares students for modern scientific and global challenges. The 20 studies analysed are summarised in Table 1.

Table 1. Evidence from Research on Pedagogies Supporting 21st-Century Skills, Instructional Strategies, and Learner Outcomes in STEM Education

Study (Year)	Research Design	Educational Level	Key Findings
Kapici et al. (2022)	2 × 2 between-subjects factorial quasi-experimental	Middle school (N = 116)	Higher guidance boosted conceptual knowledge; no effect on inquiry skills. Hands-on vs. virtual labs were equally effective.
Mutakinati et al. (2018)	Descriptive design	Japanese middle-school Grade 1 (N = 160)	Mean critical-thinking score = 2.82; 41.6% advanced, 30.6% practising, 25% beginning, 2.8% challenged thinkers.
Almulla (2020)	Survey + structural-equation modelling (SEM)	University teachers (N = 124)	PBL is significantly related to collaborative, disciplinary, iterative, and authentic learning, which in turn drives student engagement.

Study (Year)	Research Design	Educational Level	Key Findings
Wang & Li (2022)	Educational experiment	Chinese Grade 9 high school (N = 60)	Digital creativity practices improved academic performance and all five creative-thinking indicators (fluency, flexibility, originality, detail, and metaphoricity).
Jumaat et al. (2017)	Constructivist/theoretical exploration	General PjBL contexts	Project-based learning exemplifies constructivism via authentic, hands-on activities; implications for integrating constructivism in PjBL settings are discussed.
Tytlar et al. (2023)	Case studies (interviews)	Secondary schools (2 of 12; N = -)	Identified four dimensions, including design thinking in context, content integration, STEM practices, and exposure to professions, that promote mathematics engagement in integrated STEM.
Sari et al. (2020)	Pre-post investigation: student views	Undergraduate science-teaching students (N = 39)	SBIL STEM environment enhanced scientific process skills and STEM awareness; students reported increased motivation and valued simulations.
Ardianti et al. (2020a)	Quasi-experimental pretest–posttest (ANCOVA)	Rural Indonesian secondary physics	Blended STEM approach led to significantly greater critical-thinking gains vs. conventional; a unique blended/STEM framework was presented.
Ardianti et al. (2020b)	Quasi-experimental pretest–posttest (ANCOVA)	Indonesian high-school physics	Blended STEM instruction improved learning interest more than conventional methods.
Nikkola et al. (2024)	Observation + child evaluations (LI-SYC framework)	Finnish ECEC, children aged 1–7 (N = 5,047)	Creative participation correlated with skills, competencies, involvement, and play, underscores its value as a quality indicator in early childhood settings.
Osiesi & Blignaut (2025)	Descriptive survey (non-experimental)	South African pre-service teachers (N = 411)	TEC fosters collaborative, communication, critical-thinking, and creativity skills; main challenges: workload, lack of digital competence, and poor ICT assessment.
Andersen & Rustad (2022)	Mixed methods: social network analysis + interaction analysis	Higher-ed math classes using Minecraft	Minecraft use triggered collaborative learning and 21CS development; SNA + IA is effective for evaluating CSCL designs.
Behnamnia et al. (2025)	Mixed-method case study (ACCT framework + MSLQ questionnaires)	Children 3–6 in digital STEM environments	Digital STEM-based learning can enhance creative thinking, critical thinking, and motivation; fine-motor gains are observed in psychomotor tests.
Rizki et al. (2025)	Quasi-experimental (three cohorts: ESIL, ordinary inquiry, traditional)	High-school physics (N = 102)	EthnoVLab-supported inquiry was practical and aligned with objectives; ESIL group showed greater creativity and motivation gains; students responded positively.
Mou (2024)	Project-based visual storytelling; pre-post surveys + interviews	College design students (N = 48)	Creative self-efficacy and project performance improved with added creative-thinking training; motivation was unchanged; high-performers showed richer analogies.
Wilkie (2024)	Qualitative case study	Australian Year 10 (15–16 yrs)	Students showed varied creativity in problem-solving/posing tasks;

Study (Year)	Research Design	Educational Level	Key Findings
Thuneberg et al. (2018)	Pre-/post-test with path analysis	STEAM module, pupils aged 12–13 (N = 392)	preferences skewed toward problem-solving; implications for secondary math creativity tasks. Cognitive gains supported by creativity (flow > act); pre-knowledge influenced by creativity; relative autonomy and formal reasoning are also important.
Stehle & Peters-Burton (2019)	Conversion mixed method: lesson-plan/work-sample analysis	Inclusive STEM high-schools (N = 7 schools)	50/67 lesson plans included 21CS instruction (mostly introductory); higher-grade and multi-day plans exhibited more advanced skills integration.
Nouri et al. (2019)	Thematic analysis of teacher interviews	Swedish K-9 programming teachers (N = 19)	Teachers perceive the development of Brennan & Resnick CT dimensions and general 21CS (cognitive, language, collaborative, creative problem-solving).
Hsu et al. (2017)	Two AR lessons: quasi-experimental investigation + perception survey	Senior high-school (N = 32)	AR-embedded authentic inquiry (laparoscopic surgery units) increased STEM interest and positive perceptions of lessons and simulators.

Note: 21CS = 21st Century Skills; ACCT = Autonomous Creative Cognition Theory; ANCOVA = Analysis of Covariance; AR = Augmented Reality; CSCL = Computer-Supported Collaborative Learning; ECEC = Early Childhood Education and Care; ESIL = Ethno-STEM Inquiry Learning; LI-SYC = Learning and Innovation in the Sociocultural Context; MSLQ = Motivated Strategies for Learning Questionnaire; PBL = Project-Based Learning; SBIL = Simulation-Based Inquiry Learning; SEM = Structural Equation Modeling; SNA = Social Network Analysis; STEM = Science, Technology, Engineering, and Mathematics; STEAM = Science, Technology, Engineering, Arts, and Mathematics; TEC = Technological, Entrepreneurial, and Creativity education.

Findings from the SLR, as summarised in Table 1, reveal several consistent patterns regarding the cultivation of 21st-century skills through varied pedagogical approaches. Kapici et al. (2022) showed that providing higher levels of guidance in both hands-on and virtual inquiry laboratories significantly enhanced middle-school students' conceptual knowledge, although it did not affect their inquiry-skill acquisition; moreover, virtual and physical lab environments proved equally effective for conceptual and skill development. Mutakinati et al. (2018) found that Japanese middle-school students scored, on average, 2.82 in critical-thinking assessments, with over 40 per cent qualifying as advanced thinkers. This suggests that STEM-based, project-driven tasks can foster higher-order reasoning.

Project-based and constructivist frameworks emerged as powerful drivers of engagement and creativity. Almulla's Structural Equation Modelling analysis (2020) confirmed that PBL correlates strongly with collaborative, disciplinary, iterative, and authentic learning, which in turn boosts student engagement. Wang and Li (2022) demonstrated that digital creativity practices significantly improved high-school students' performance across all five creative-thinking dimensions, fluency, flexibility, originality, detail, and metaphoricality. Jumaat et al. (2017) discussed how project-based learning embodies constructivist principles through authentic, hands-on activities, while Tytler et al. (2023) identified four dimensions that promote mathematical engagement in integrated STEM contexts.

Simulation-based inquiry and blended-STEM approaches consistently enhanced both skills and attitudes. Sari et al. (2020) reported that undergraduates in a simulation-based inquiry learning environment displayed marked improvements in scientific-process skills and STEM awareness, coupled with increased motivation. Ardianti et al. (2020a, b) found that a rural Indonesian blended-learning framework embedded in STEM education produced significantly greater gains in critical thinking and learning interest than conventional methods. In early childhood, Nikkola et al. (2024) showed that creative participation correlates with children's skills, competencies, involvement, and play, highlighting its importance as an indicator of quality in ECEC settings. Osiesi and Blignaut (2025) observed that South African pre-service teachers

perceive their curriculum as largely effective at nurturing collaboration, communication, critical thinking, and creativity, despite challenges such as workload and digital-competency gaps.

The integration of digital and immersive technologies further amplified collaborative and creative outcomes. Andersen and Rustad (2022) demonstrated that using Minecraft as an educational tool in higher-education maths classes triggered collaborative learning processes and supported the development of 21st-century skills, with SNA and interaction analysis proving effective for evaluation. Behnamnia et al. (2025) reported that digital STEM-based environments enhanced young children's creative and critical-thinking skills, motivation, and fine-motor development. Rizki et al. (2025) showed that EthnoVLab-supported inquiry in physics significantly boosted high-school students' creativity and motivation compared to ordinary and traditional methods. In tertiary design education, Mou (2024) found that adding creative-thinking training to visual storytelling projects improved students' creative self-efficacy and project performance, though motivation remained stable. Wilkie (2024) and Thuneberg et al. (2018) highlighted that problem-solving and STEAM modules elicit diverse creative responses and that 'flow' creativity most strongly predicts cognitive gains in mathematics.

Finally, Hsu et al. (2017) demonstrated that embedding augmented reality in authentic inquiry lessons, specifically medical-surgery simulations, increases senior-high students' STEM interest and positive perceptions of both the lessons and simulators. Taken together, these findings suggest that carefully scaffolded guidance, student-centred and project-based strategies, blended and immersive technologies, and constructivist frameworks can synergistically foster critical thinking, creativity, collaboration, and digital literacy across educational levels in STEM.

5. DISCUSSION

The discussion of the findings is presented here in relation to previous review papers on 21st-century skills and instructional strategies in STEM. Early syntheses of critical-thinking development, such as Carter et al. (2016), highlighted considerable variability in the efficacy of teaching interventions and underscored the need for discipline-specific tools to measure critical thinking within authentic practice contexts. Similarly, umbrella reviews of extended reality (XR) in STEM, exemplified by Zhang et al. (2024), have demonstrated clear benefits for motivation and engagement but have also noted persistent challenges around learner comfort and technical reliability. Building on these foundational reviews, our findings from the systematic analysis of 20 primary studies extend understanding of how diverse pedagogies foster 21st-century competencies.

Findings from the review confirm that inquiry-based and project-based frameworks remain powerful levers for cultivating critical thinking and collaboration. For instance, Saad and Zainudin (2022) found that effective PBL-CT integrations hinge on scaffolding and visual-tool support, yet no single model has achieved consensus across contexts. Halawa et al. (2020) observed that student-centred strategies, particularly experimentation and discussion, have grown in prominence over the past decade, yielding large positive effects on cognitive outcomes. These findings resonate with Ünlü and Dökme's (2022) critique of the 5E model's traditional focus on lower-order thinking, prompting their proposal of a skill-based STEM instructional model that explicitly targets higher-order competencies.

The integration of digital and immersive technologies consistently amplifies learner engagement and creative outcomes. Ibáñez and Delgado-Kloos (2018) noted that augmented-reality applications predominantly support exploration and simulation but often lack metacognitive scaffolds. In line with this, Kumar et al. (2023) emphasised AI and metaverse platforms as emerging frontiers for personalised feedback and adaptive learning, while cautioning against ethical and privacy concerns. Synthesis from this study builds on these insights by showing that when virtual and hands-on laboratories are equally supported with adequate guidance, conceptual gains are maximised without sacrificing inquiry skills (Kapici et al., 2022; Mutakinati et al., 2018).

Integrated STEM approaches further underscore the value of interdisciplinary collaboration. Martín-Páez et al. (2019) indicated that various interpretations of STEM in empirical research frequently prioritise subject-specific factors instead of genuine integration. Le et al. (2023) differentiated between in-curriculum and out-of-school STEM PBL, showing distinct impacts on higher-order thinking versus career interest.

The findings of this study corroborate this nuance: programmes that blend engineering-design processes with authentic projects (e.g., EthnoVLab, Rizki et al., 2025) yield significant creativity and motivation gains, whereas generic PBL contexts may under-deliver unless carefully contextualised.

In addition, equity and inclusivity emerge as critical considerations. González-Pérez (2022) highlighted the absence of Education 4.0 frameworks for teachers and schools, noting most efforts target student competencies alone. Adeduyigbe et al. (2024) called attention to the specific needs of learners with hearing impairments, arguing for tailored strategies and assistive technologies. This review reiterates these priorities by illustrating that blended-STEM and simulation-based inquiry can be potent equalisers when accompanied by professional development and resource support. This suggests that transformative science education depends on the strategic alignment of scaffolded inquiry, immersive technologies, interdisciplinary projects, and equity-centred design.

5.1. Implications of Findings from the Review

The implications of these findings resonate across research, policy, and practice. For researchers, the demonstrated value of scaffolded inquiry and immersive technologies points to the need for studies that combine quantitative and qualitative methods to capture both conceptual gains and changes in motivation, collaboration, and self-regulated learning. Longitudinal designs will be essential to understand how 21st-century skills evolve, while comparative investigations of virtual versus hands-on laboratory experiences under consistent support structures can clarify the most effective balance for both content mastery and inquiry skill development.

Policymakers and curriculum developers can draw on this synthesis to shape more inclusive and future-focused STEM frameworks. By embedding interdisciplinary, project-based modules within official standards and by instituting professional development requirements for teachers in both extended-reality tools and equity-centred strategies, system leaders can ensure that innovations reach all learners. Curriculum guidelines might include explicit expectations for metacognitive scaffolds in digital environments and for the provision of assistive technologies to accommodate diverse needs.

At the school level, leaders and practitioners can pilot blended-STEM initiatives that pair virtual and physical laboratories with structured reflection prompts and collaborative problem-solving tasks. Regular peer-learning communities among educators will help to share effective practices in project-based learning and technology integration. Finally, funders and district teams should prioritise scaling up small-scale interventions that have shown impact on critical thinking and creativity, and they should support the creation of open-access repositories of validated tools for assessing 21st-century competencies.

6. CONCLUSION, LIMITATIONS, AND FUTURE RESEARCH DIRECTIONS

This review reveals that transformative science education relies on the strategic integration of scaffolded inquiry, project-based frameworks, immersive technologies, and interdisciplinary STEM projects. When carefully supported with metacognitive prompts and professional development, these strategies foster critical thinking, creativity, collaboration, and digital literacy across educational levels. Equity-centred designs, including assistive technologies and targeted teacher training, are essential to ensure that innovations benefit all learners. By aligning pedagogical models with 21st-century skill imperatives and embedding them within policy frameworks, educators and system leaders can drive sustainable improvements in student engagement and learning outcomes.

Although findings from this review are shaped by the scope and quality of existing empirical work, we must acknowledge certain limitations of the research. First, because the synthesis is based on only published studies in English, there is a risk of language and publication bias, which may over-represent positive or well-resourced interventions. Second, our reliance on secondary data means we cannot verify original measurement procedures or control for unreported contextual factors; heterogeneity in study designs, assessment tools, and reporting standards limits comparability and generalisability. Third, many primary studies are of short duration and employ single-site or convenience samples, hindering insights into the long-term durability of 21st-century skill gains or wider applicability.

Therefore, future research should address these gaps by designing longitudinal, mixed-method, and multi-site studies that track learners over time and across diverse contexts. Comparative trials that isolate virtual versus hands-on experiences under consistent scaffolding will clarify optimal blends of technology and pedagogy. The development and validation of discipline-specific instruments for assessing critical thinking, creativity, and collaboration will improve measurement precision. Finally, large-scale intervention studies in underrepresented regions and multilingual settings are needed to ensure equitable applicability and to inform scalable policy and practice.

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Research Ethics. This study is a systematic literature review and did not involve human participants, animals, or identifiable personal data; consequently, ethical approval was not required. All included studies were previously published in peer-reviewed journals, and their authors had obtained any necessary permissions. The authors adhered to established guidelines for conducting and reporting reviews, ensuring that sources were accurately represented and cited in accordance with ethical standards.

Data Availability Statement. This research does not involve primary numerical data. All information presented has been drawn from and correctly cited to previously published sources. Consequently, no new datasets were generated or analysed for this study. Readers may refer to the original publications for underlying data and further details.

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