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ADVANCING PHYSICS AND SCIENCE EDUCATION THROUGH INNOVATIVE TECHNOLOGIES AND PEDAGOGICAL STRATEGIES

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Abstract:

Physics education continues to face persistent challenges, including abstract content, entrenched misconceptions, and declining student engagement. Recent innovations in technology, pedagogy, assessment, and curriculum offer opportunities to address these issues, but their impact depends on coherent integration rather than isolated adoption. Drawing on 52 articles published between 2010 and 2025, this review synthesizes developments across five thematic domains: technological innovations, pedagogical strategies, teacher professional development, assessment practices, and curriculum integration. The findings highlight that tools such as virtual laboratories, artificial intelligence, and AR/VR environments can expand inquiry-based learning, yet they require strong pedagogical grounding to move beyond novelty. Active, inquiry-oriented, and collaborative strategies enhance conceptual understanding but remain resource-intensive. Teacher professional development emerges as the linchpin of sustainable reform, underscoring the need for iterative, reflective, and practice-oriented models that strengthen pedagogical content knowledge and professional identity. Assessment practices must evolve from reliance on concept inventories toward authentic, technology-enhanced approaches that capture higher-order competencies. Curriculum reform, through interdisciplinary STEM links and sustainability themes, provides systemic opportunities but also raises concerns regarding equity and scalability. This review concludes that meaningful transformation in physics education requires coherence across technologies, pedagogies, assessments, and curricula.

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Introduction

Physics education is often perceived as abstract and conceptually demanding, with many students struggling to connect theoretical principles to real-world experiences (Kadiri & Hodolli, 2025; Martínez-Borreguero et al., 2024). Misconceptions in core areas such as force, optics, and energy are widespread and tend to persist when instruction relies heavily on traditional didactic approaches that emphasize rote problem-solving rather than conceptual reasoning (Etkina et al., 2003). Such challenges contribute to student disengagement, declining enrollment in physics courses, and reduced interest in pursuing STEM-related careers (Ragadhita et al., 2025).

Addressing these issues requires more than surface-level reforms. Recent scholarship highlights the potential of emerging technologies to provide immersive, personalized, and interactive learning opportunities. At the same time, pedagogical strategies grounded in inquiry, collaboration, and active engagement have demonstrated the capacity to restructure how physics is both taught and learned. Importantly, innovation must not be limited to the adoption of new tools and techniques; it also involves rethinking teacher preparation, curriculum design, and equity-focused practices that nurture scientific literacy and 21st-century competencies (Varis et al., 2018; Bustamante & Urrego, 2025).

Accordingly, this review synthesizes contemporary scholarship on innovation in physics education across five interrelated dimensions. It first analyzes the role of virtual and digital technologies in reshaping how physics is taught and learned, before evaluating pedagogical strategies that address misconceptions and foster deeper conceptual engagement. Attention is then given to teachers as central mediators of innovation, assessing their professional development needs and preparedness to integrate new tools and approaches. The review further examines assessment practices, considering how validated instruments and technology-enhanced approaches can be aligned with innovative pedagogies to support conceptual understanding and student engagement. Finally, it explores curriculum development and integration, highlighting the ways interdisciplinary STEM connections, sustainability themes, and emerging technologies can be embedded into physics education in equitable and pedagogically grounded ways.

Literature

Innovative pedagogies have become essential in modern education, aiming to enhance critical thinking, creativity, and problem-solving skills among students. However, the implementation of these pedagogies faces several challenges, including teacher preparedness, technological limitations, and socio-cultural resistance (Awang et al., 2025). To overcome these barriers, comprehensive interventions such as targeted professional development, strategic investments in infrastructure, and culturally responsive strategies are necessary. The integration of modern educational technologies, such as information and communication technologies (ICT), has shown promise in improving the effectiveness of physics education by making learning more interactive and accessible (Malik, 2023; Kalpachka, 2020).

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The use of technology in education has been shown to positively impact student learning outcomes, including academic achievement, knowledge retention, and critical thinking skills (Malik, 2023). Technology-based education also enhances student engagement and motivation, leading to improved teacher-student interactions 3. For instance, the implementation of game-based and video-based instruction has been found to significantly improve students' scientific knowledge and argumentation skills compared to traditional instruction methods (Chen et al., 2021). Additionally, the use of high-tech equipment in experimental activities helps students gain a comprehensive understanding of physical concepts, further enhancing the quality of physics education (Hamamous & Benjelloun, 2023; Kanyesigye et al., 2022).

Emerging technologies such as augmented reality (AR), virtual reality (VR), and intelligent tutoring systems have the potential to transform physics education by providing immersive and interactive learning experiences (Prahani & Dawana, 2025; Daineko et al., 2017). These technologies help students understand abstract concepts and increase their engagement in learning. For example, AR and VR have been shown to improve students' understanding of complex physics topics and foster 21st-century skills. Moreover, the use of AI-driven adaptive learning systems and gamified learning platforms can personalize the learning experience, catering to individual student needs and promoting deeper learning (Milala et al., 2025).

Despite the benefits, integrating technology into education presents challenges such as the need for technical support, potential distractions, and the necessity for teacher training (Aggarwal et al., 2024; Malik, 2023). To address these issues, it is crucial to develop a cohesive understanding of how to effectively harness these technologies to create learner-centric and engaging learning experiences (Aggarwal et al., 2024). Future research should focus on longitudinal studies of teacher training, AI-driven adaptive learning pilots, and competency-based policy evaluations to ensure the sustainable and equitable adoption of innovative pedagogical practices (Awang et al., 2025). Additionally, fostering collaboration among educators, policymakers, and technology developers is essential for the successful integration of technology in education (Awang et al., 2025; Aggarwal et al., 2024).

In conclusion, advancing physics and science education through innovative technologies and pedagogical strategies holds significant promise for enhancing student learning outcomes and engagement. However, addressing the challenges associated with their implementation requires comprehensive interventions, continuous research, and collaboration among stakeholders.

Methodology

This review employed the Scopus database, selected for its wide coverage of peer-reviewed journals in science and education. A systematic search was conducted using the keywords "physics education" AND "innovative technology", which initially retrieved 200 records. A multi-step screening process was applied to ensure relevance and quality. First, the search was restricted to publications between 2010 and 2025. Second, only journal articles were included, with duplicates and non-research documents (e.g., conference proceedings, books, reports, and editorials) excluded. Third, only articles published in English were retained. Finally, full-text assessments were carried out to confirm alignment with the scope of this study, namely innovations in physics education. After applying these criteria, 52 journal articles remained eligible. The review process followed the PRISMA framework (Moher et al., 2009) and is summarized in Figure 1.

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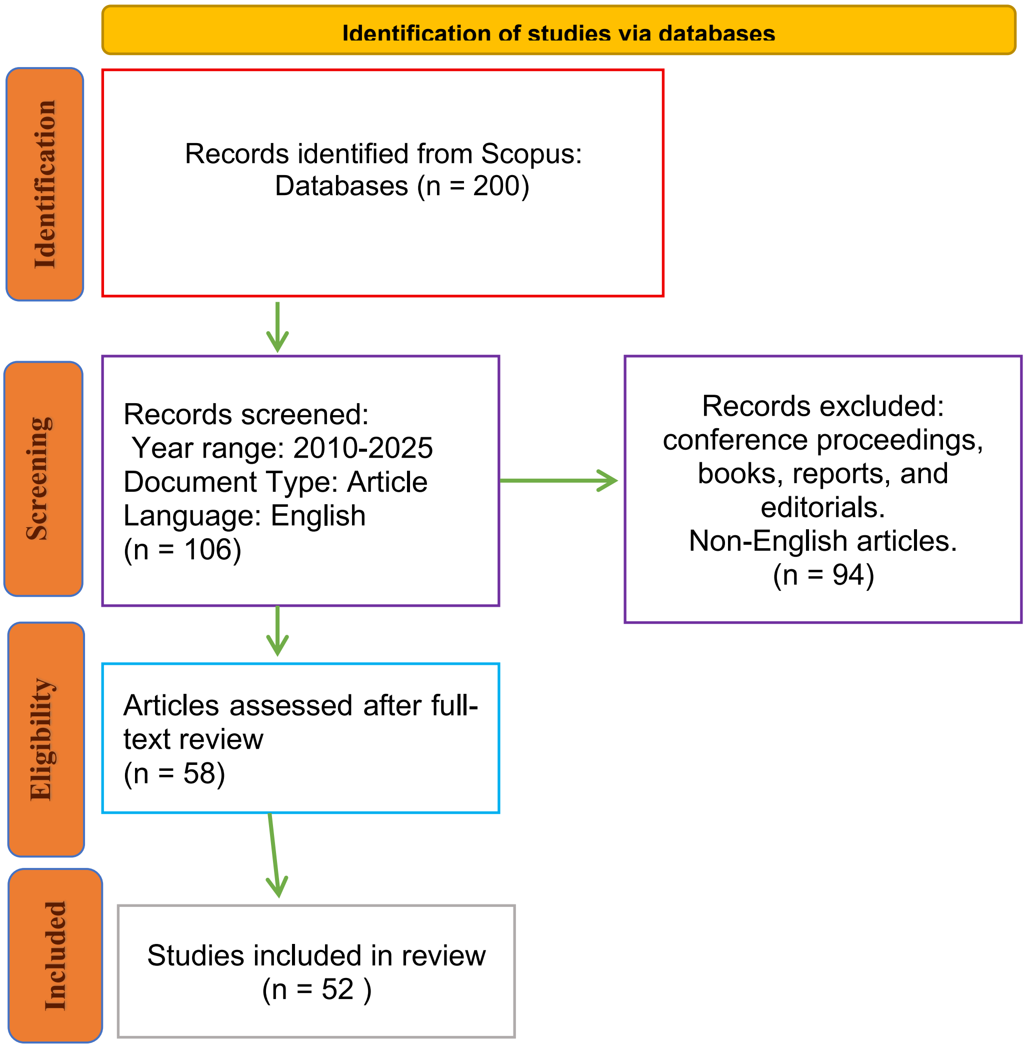
Figure 1: PRISMA Style Flow Diagram of the Review Process



A qualitative content analysis approach was adopted. Each study was coded for its objectives, research problems, methods, results, and recommendations, based on a tabular matrix developed for this review. The coding process followed the phases of familiarisation, theme generation, and synthesis (Braun & Clarke, 2006). Through this iterative process, five thematic domains were identified as central to innovation in physics education.

Findings

The review of literature reveals five major domains through which innovation is shaping physics education in terms of: technological integration, pedagogical strategies, teacher professional development, assessment practices, and curriculum design. These domains are interconnected, collectively addressing long-standing challenges such as abstract content, persistent misconceptions, limited student engagement, and inequities in access to quality learning opportunities. The following Table 1 summarised the distribution of reviewed study,

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drawing on current evidence to identify both opportunities and challenges in advancing physics education.

Table 1: Summary of the Distribution of Reviewed Studies Across Five Domains of Innovation in Physics Education

Domain	Number of Studies	Representative Authors
Technological Innovations	27	Casamayou et al. (2025); Guo et al. (2025); Perez-Linde & Cárdenas (2025); Ragadhita et al. (2025); Prahani et al. (2024) Malik (2023); Franco et al. (2023) ; Hussaini et al. (2023); Diep et al. (2023) Kasimakhunova & Umarova, 2023); Mukhtarkyzy et al. (2022); Prahani et al. (2022) Jesionkowska et al. (2020); Iqbal & Sami (2020); Aşıksoy, (2019); Sabirova et al. (2019) Lo et al. (2018); Daineko et al., 2017; Sun et al. (2017); Lindgren et al. (2016); Bhatal (2016); Gryczka et al. (2016); Sulisworo et al. (2016) Saidin et al. (2015); Taub et al. (2015); Chang et al., 2015 Fakomogbon et al. (2014); Myneni et al., 2013
Pedagogical Strategies	12	Li (2025); Lichtenberger (2025) Yang & Chen (2024); Martínez-Borreguero et al. (2024) Akimkhanova et al. (2023) Rodríguez-Martín et al. (2020) Auyuanet et al. (2018); Eshach et al. (2018) Lo et al. (2018) Kapon (2016); Sulisworo et al. (2016); Dilber (2010)
Teacher Preparation and Professional Development	9	Darman (2025); Isaeva et al. (2025); Nurhayati et al. (2025); Falebita (2025); Melweth et al. (2024); Lindfors et al. (2020); Gunnarsson et al. (2018); Keller et al. (2017) Alonzo & Kim, 2016
Assessment and Engagement	8	Kadiri et al. (2025); Martínez-Borreguero et al. (2024) Vignal et al. (2023); Mukhtarkyzy et al. (2022) Siersma et al., (2021); Sands et al. (2018); Varis et al. (2018); Gomes et al. (2016)
Curriculum Development and Integration	10	Basheer et al. (2025); Bui et al., et al. (2025) Salmoiraghi et al. (2025); Perez-Linde & Cárdenas (2025) Martínez-Borreguero et al. (2024); Prahani et al. (2024); Diep et al. (2023); Jesionkowska et al. (2020); Lindfors et al., 2020; Byers et al (2010)

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Technological Innovations in Physics

Technological advances have provided powerful platforms for reimagining how physics content is introduced, explored, and assessed. The shift from passive reception of knowledge to interactive engagement has been accelerated by innovations such as virtual laboratories, augmented and virtual reality (AR/VR), artificial intelligence (AI), and online learning platforms. Collectively, these tools open new possibilities for enhancing conceptual understanding, but they also raise questions about access, sustainability, and teacher preparedness.

Virtual and Remote Laboratories

Simulated laboratories allow learners to explore physical phenomena in safe, flexible, and cost-effective environments. Systems such as SHIRE, an adaptive optical simulation platform, enable students to manipulate variables and observe immediate outcomes, fostering autonomy in optics learning (Casamayou et al., 2025; Daineko et al., 2017). Advanced tools such as SHIRE enable self-adaptive optical simulation and foster collaborative learning environments, enhancing autonomy in optics education (Casamayou et al., 2025). Remote laboratories extend these affordances by enabling students to control real experimental apparatus online, a feature that proved especially valuable during the COVID-19 pandemic (Franco et al., 2023; Hussaini et al., 2023). While such platforms democratize access for geographically dispersed or under-resourced schools, critics note that they risk diminishing the tactile experiences essential to laboratory practice.

Augmented and Virtual Reality

AR and VR offer distinctive ways of visualizing abstract concepts in physics. AR overlays digital elements onto real contexts, supporting embodied cognition by making invisible processes, such as current flows or planetary motion, more concrete (Mukhtarkyzy et al., 2022; Jesionkowska et al., 2020; Saidin et al., 2015). VR extends this potential by immersing learners in fully simulated environments. For example, mixed-reality simulations in gravity lessons have been shown to boost both engagement and conceptual understanding (Lindgren et al., 2016). However, despite these pedagogical benefits, implementation remains uneven due to cost barriers, infrastructure limitations, and varying levels of institutional support.

Artificial Intelligence and Intelligent Systems

AI applications are increasingly shaping physics education through adaptive tutoring, automated feedback, and intelligent programming platforms. Early exposure to AI-based systems can encourage independent exploration and higher-order reasoning, as demonstrated in undergraduate contexts (Perez-Linde & Cárdenas, 2025; Guo et al., 2025; Prahani et al., 2024). Intelligent tutoring systems such as ViPS help diagnose misconceptions and provide targeted feedback (Aşıksoy, 2019; Myneni et al., 2013). Nonetheless, concerns have been raised about students' over-reliance on AI, as well as the limited capacity of teachers to effectively integrate these systems into classroom practice (Guo et al., 2025).

Multimedia and Online Learning Platform

Digital platforms continue to play a crucial role in expanding access and diversifying modes of learning. Computer assisted learning (Malik, 2023; Aşıksoy, 2019; Taub et al., 2015) and learning management systems (e.g., Moodle) support blended and classroom approaches, allowing students to engage asynchronously with content (Lo et al., 2018; Kasimakhunova & Umarova, 2023). Video annotation platforms further enhance collaborative reflection on

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experiments and theoretical explanations (Marçal et al., 2020). Despite these affordances, inequities in device access, internet connectivity, and teacher readiness remain pressing challenges, particularly in under-resourced contexts.

Table 2: Technological Innovations in Physics Education: Benefits and Challenges

Technology	Benefits	Limitations/Challenges
Virtual Labs	Cost-Effective, safe, scalable	Lack tactile engagement
Remote Labs	Extend access, crisis-resilient	Require internet infrastructure
AR/VR	Embodied, immersive cognition	High cost, limited scalability
AI Tutors	Personalized scaffolding, misconception diagnosis	Teacher preparedness, dependency risks
Multimedia	Flexible, collaborative, asynchronous learning	Digital divide, training needs

Taken together, these strands of innovation highlight a clear trajectory toward more interactive and student-centered physics learning. Yet the literature also emphasizes persistent limitations, suggesting that technological innovation alone is insufficient without parallel attention to pedagogy, equity, and teacher professional development. Table 2 shows the summary of technological innovation in physics education.

Pedagogical Strategies in Physics Education

Technology alone does not guarantee meaningful learning; its effectiveness depends on being coupled with progressive pedagogical strategies. A large body of research demonstrates that active approaches significantly improve student outcomes, with evidence showing that active learning reduces failure rates by 33% compared with traditional lectures (Auyuanet et al., 2018). Beyond performance gains, inquiry-driven strategies nurture epistemic growth by engaging students in the construction and justification of scientific explanations.

Active and Inquiry-Based Learning

Programs such as FísicActiva illustrate how structured opportunities for active participation enhance cognitive activation and promote deeper understanding (Auyuanet et al., 2018). Inquiry-oriented designs are particularly effective for addressing entrenched misconceptions, as they guide students to test and reconstruct mental models under teacher scaffolding (Kapon, 2016). Yet, inquiry learning is resource-intensive, requiring significant instructional time and sustained teacher facilitation, which may limit scalability in standard classroom contexts.

Flipped Classrooms and Blended Learning

Flipped classrooms shift initial content acquisition to out-of-class spaces, freeing up classroom time for higher-order application. Meta-analyses confirm their positive effects on autonomy, motivation, and knowledge retention (Yang & Chen, 2024). When integrated with cooperative learning through learning management systems (LMS), blended designs extend collaboration and flexibility, making learning more interactive (Sulisworo et al., 2016). While student performance in the flipped ICT course was comparable to that of the non-flipped ICT course, flipping other subjects, such as mathematics, physics, and Chinese language led to improvements in achievement, with effect sizes ranging from small to moderate (Lo et al., 2018). However, these approaches presuppose consistent student self-regulation and equitable access to digital devices, raising concerns about widening achievement gaps in contexts where resources are unevenly distributed.

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Conceptual Change Approaches

Persistent misconceptions remain a central barrier in physics education, particularly in domains such as sound propagation and optics (Eshach et al., 2018; Martínez-Borreguero et al., 2024; Rodríguez-Martín et al., 2020). Conceptual change pedagogy directly targets these issues through analogies, demonstrations, and formative assessment, encouraging students to replace intuitive but flawed models with scientifically accepted explanations (Lichtenberger et al., 2025; Dilber, 2010). While effective, these interventions require careful design to avoid reinforcing the very misconceptions they aim to displace.

Collaborative and Student-Centered Learning

Collaborative formats; including peer-led projects, research-based assignments, and game-based interventions, have been shown to strengthen motivation, social participation, and authentic engagement in physics learning (Li, 2025; Akimkhanova et al., 2023; Kapon, 2016). Such approaches shift responsibility for learning onto students, promoting agency and teamwork. The challenge, however, is ensuring that collaboration does not devolve into superficial "edutainment" but remains tied to clearly articulated curricular outcomes and rigorous disciplinary understanding.

Collectively, these pedagogical innovations highlight the importance of moving beyond transmission models of teaching. While each approach offers distinct affordances, they converge on the principle that meaningful learning in physics emerges from student-centered, inquiry-rich, and socially mediated experiences. Table 3 below shows the summary of pedagogical strategies and learning outcomes in physics education.

Table 3: Pedagogical Strategies and Learning Outcomes

Strategy	Key Outcomes	Critical Issues
Active Learning	Higher engagement, reduced failure rates	Classroom redesign required
Inquiry-Based	Supports critical thinking, conceptual repair	Time/resource heavy
Flipped Classroom	Enhances autonomy, motivation	Digital inequity, resistance
Conceptual Change	Corrects persistent misconceptions	Requires diagnostic tools
Collaborative/Game-Based	Increases motivation, teamwork	Risk of trivialization

Teacher Preparation and Professional Development

Teachers are the pivotal mediators of educational innovation. Even when advanced technologies are available, their classroom impact ultimately depends on teachers' ability to integrate them into meaningful pedagogy. However, research shows that many teachers, while theoretically aware of innovative practices, lack the practical competencies required for sustained technology integration (Isaeva et al., 2025; Nurhayati et al., 2025). This gap underscores the importance of professional development (PD) that moves beyond surface familiarity with tools to the deeper cultivation of pedagogical expertise and confidence.

Technology Integration and Skills Gap

Much current professional development remains fragmented, emphasizing one-off training in tool usage rather than iterative cycles of design, implementation, and reflection (Nurhayati et al., 2025). Consequently, teachers often experience difficulties translating new technologies

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into authentic classroom practice. Anxieties around programming or AI tools can further undermine confidence, reinforcing reluctance to experiment (Falebita, 2025; Melweth et al., 2024). Comprehensive PD must therefore target not just technical proficiency, but also the capacity to adapt technologies flexibly to diverse learning contexts.

Pedagogical Content Knowledge and Beliefs

Central to effective innovation is teachers' pedagogical content knowledge (PCK), the ability to integrate subject matter expertise, pedagogical strategies, and an understanding of students' cognitive challenges (Lindfors et al., 2020; Alonzo & Kim, 2016). Teachers with well-developed PCK are able to diagnose misconceptions, scaffold learning, and align instruction with epistemic goals. In contrast, those with weaker PCK risk reinforcing students' naïve models despite using innovative tools. PD programs that explicitly cultivate PCK, particularly through reflection on student thinking, are critical for maximizing the benefits of new technologies.

Motivation and Professional Identity

Teacher motivation and professional identity also shape the effectiveness of innovation. Studies show that teacher attitudes strongly correlate with students' engagement and achievement (Keller et al., 2017). Professional development should therefore be conceived not only as skill-building but also as a means of nurturing resilience, identity, and agency. Supporting teachers through mentorship and gradual adoption strategies can help alleviate anxieties, sustain motivation, and build confidence in navigating change (Gunnarsson et al., 2018).

Synthesis of Needs and Directions

Table 4 summarizes the recurrent challenges and potential directions for teacher professional development. These include iterative, hands-on PD cycles for technology integration; greater emphasis on PCK through video-based reflection and peer coaching; targeted support for teacher motivation through mentorship; and the explicit embedding of 21st-century skills (communication, collaboration, creativity, critical thinking) into teacher preparation programs.

Table 4: Teacher Professional Development Needs

Focus Area	Current Challenges	Recommendations
Technology Integration	Fragmented training, theory > practice	Iterative, hands-on PD cycles
PCK Development	Limited focus on student thinking	Video-based reflection, peer coaching
Teacher Motivation	Tech-related anxieties	Mentorship, gradual adoption
4C Skills	Underemphasized in training	Embed explicitly in teacher preparation

Assessment and Engagement

For innovation in physics education to be meaningful, assessment practices must evolve in tandem with new pedagogies and technologies. Yet, in many contexts, assessment continues to prioritize rote memorization and algorithmic problem-solving, which undermines efforts to foster higher-order thinking, creativity, and authentic engagement. A shift toward more holistic and technology-enabled assessment strategies is therefore central to sustaining innovation.

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Validated Assessment Tools

Concept inventories, such as the Force Concept Inventory, alongside psychometrically validated surveys, remain widely used for reliably capturing conceptual understanding (Martinez-Borreguero et al., 2024; Siersma et al., 2021; Vignal et al., 2023; Sands et al., 2018). Their strength lies in producing consistent, comparable data that helps track learning gains. However, these instruments are limited in scope, as they do not capture broader competencies such as creativity, collaboration, or epistemic reasoning, skills increasingly emphasized in 21st-century physics education.

Authentic and Technology-Enhanced Assessment

To address these limitations, researchers and practitioners have turned to authentic and technology-enhanced assessments. Game-based platforms and augmented reality (AR) applications provide immersive environments in which learners can demonstrate conceptual and problem-solving skills in realistic contexts (Mukhtarkyzy et al., 2022; Gomes et al., 2016). Such approaches align assessment more closely with the complex, situated nature of scientific inquiry, and they also tend to increase student motivation and engagement (Varis et al., 2018). However, challenges remain, including issues of standardization, institutional acceptance, and scalability across diverse educational systems.

Synthesis of Approaches

Table 4 summarizes the strengths and weaknesses of the major assessment approaches currently documented in physics education. The literature suggests that no single tool is sufficient; instead, hybrid models that combine validated inventories with authentic, technology-driven tasks may provide a more balanced picture of student learning.

Table 4: Assessment Approaches in Physics Education

Assessment Method	Strengths	Weaknesses
Concept Inventories	Valid, reliable	Narrow focus
Pre/Post Tests	Track conceptual gains	Limited depth
Surveys & Reflections	Capture attitudes, perceptions	Bias, subjectivity
AR/Game-Based	Authentic, motivating	Difficult to standardize

Curriculum Development and Integration

Interdisciplinary STEM curricula increasingly highlight the value of linking physics with engineering, mathematics, and broader societal concerns (Diep et al., 2023). Such integration reflects a recognition that physics knowledge gains relevance when situated within authentic contexts and cross-disciplinary problem-solving (Salmoiraghi et al., 2025). Programs that embed sustainability themes are particularly effective in demonstrating relevance and fostering student engagement. Yet, the literature makes clear that scaling such initiatives requires more than curricular design; it demands sustained institutional commitment and policy-level support (Basheer et al., 2025; Bui et al., et al., 2025). Without these systemic enablers, curriculum innovation risks remaining confined to isolated pilot projects rather than becoming mainstream practice.

Inclusion of Emerging Technologies

The incorporation of emerging technologies, such as AI, AR, and programming, into physics curricula signals a paradigm shift in science education. These tools do more than enhance visualization; they increasingly mirror the authentic practices of contemporary scientists,

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offering students opportunities to engage in inquiry that resembles real-world research. For instance, AI-driven adaptive platforms provide immediate feedback and tailored scaffolding, allowing learners to progress at their own pace while addressing misconceptions in real time (Perez-Linde & Cárdenas, 2025; Prahani et al., 2024). Attention to cultural, gender, and cognitive diversity within curriculum design ensures inclusiveness and responsiveness to varied student needs (Martinez-Borreguero et al., 2024). Similarly, AR and VR environments immerse students in representations of otherwise abstract or inaccessible phenomena, such as wave interference or electromagnetic fields (Jesionkowska et al., 2020).

However, the literature cautions against an uncritical embrace of these innovations. When integrated without strong pedagogical grounding, technologies risk being reduced to superficial novelties rather than vehicles for deep conceptual and epistemological learning. More troublingly, curricular integration of advanced technologies can exacerbate inequities: students in underfunded schools often lack access to the required infrastructure, perpetuating rather than reducing disparities. This suggests that the value of emerging technologies lies not only in their design but in the systems that support their equitable use.

Moving forward, curriculum innovation in physics must therefore operate on two levels. At the classroom level, it requires explicit alignment of emerging technologies with inquiry-based, conceptually rich pedagogies. At the systemic level, it demands robust teacher training, institutional investment, and curricular frameworks that explicitly connect these tools to broader epistemic and societal goals. Only through this dual emphasis can curriculum development move beyond isolated experiments and achieve sustainable, equitable transformation in physics education.

Discussion

The synthesis of technological, pedagogical, professional, assessment, and curricular innovations in physics education highlights both opportunities and persistent challenges. At a theoretical level, these findings resonate strongly with constructivist perspectives, which position learning as an active process of constructing meaning rather than passively receiving information (Piaget, 1970; Vygotsky, 1978). Innovations such as virtual laboratories, inquiry-based approaches, and authentic assessments are most effective when they create opportunities for students to actively test, refine, and negotiate ideas in social and reflective contexts (Safaryan, 2023). This confirms that technology or curricular reform in isolation is insufficient; innovation must be pedagogically grounded and theoretically coherent.

At a practical level, the reviewed studies converge on a shared set of priorities: addressing misconceptions, improving engagement, and cultivating 21st-century skills such as collaboration, creativity, and critical thinking (Jamil et al., 2024; Verawati & Nisrina, 2025). For instance, AR/VR environments help students visualize abstract phenomena, but their true pedagogical power emerges when embedded within inquiry cycles that challenge and reconstruct misconceptions (Jesionkowska et al., 2020; Lindgren et al., 2016). Similarly, flipped classrooms and blended learning extend engagement opportunities, though their success depends on equitable access to resources and students' capacity for self-regulated learning (Yang & Chen, 2024; Sulisworo et al., 2016). Teacher professional development consistently emerges as the linchpin of sustainable innovation. Without teachers who are confident, motivated, and equipped with strong pedagogical content knowledge, innovations risk superficial adoption or abandonment (Sulaimon & Adebayo, 2024; Isaeva et al., 2025).

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Implications for physics education therefore extend across multiple levels. In classrooms, teachers need iterative, practice-oriented professional development that links emerging technologies to strategies for conceptual change (Nurhayati et al., 2025; Keller et al., 2017). At the institutional level, curriculum reform should embed interdisciplinary STEM connections and sustainability themes, ensuring that technology integration is equitable and grounded in explicit epistemic goals (Diep et al., 2023; Gamage et al., 2022). Finally, assessment reform must evolve alongside instructional innovation. Traditional tools such as concept inventories provide reliability but fail to capture broader competencies; authentic and technology-enhanced assessments offer promise but face challenges of institutional acceptance and standardization (Sands et al., 2018; Mukhtarkyzy et al., 2022). Taken together, these implications point toward a vision of physics education as more interactive, student-centered, and socially relevant.

Nonetheless, this review is subject to several limitations. The scope of sources, while diverse, is not exhaustive; it reflects literature accessible in selected databases, which may underrepresent innovations reported in non-English contexts. The analysis is also constrained by the reporting quality of primary studies, many of which emphasize positive outcomes without addressing scalability or long-term sustainability. Moreover, this review employed thematic synthesis rather than meta-analysis, which means the strength of effects across interventions cannot be compared systematically. Future research should therefore include cross-national perspectives, longitudinal studies of implementation, and mixed-methods syntheses that integrate statistical effect sizes with qualitative insights (Eshach et al., 2018; Clarke et al., 2022).

In sum, the discussion underscores that transforming physics education requires more than the adoption of isolated tools or strategies. Sustainable change demands systemic alignment of technologies, pedagogies, teacher preparation, assessment practices, and curricula, anchored in constructivist principles and equity-driven practices. Only through such integration can physics education cultivate conceptual mastery, scientific literacy, and problem-solving skills essential for the twenty-first century.

Conclusion

The objectives of this review were to examine technological innovations, pedagogical strategies, teacher preparation, assessment practices, and curricular reforms in physics education. These objectives were achieved by synthesizing 58 peer-reviewed studies published between 2010 and 2025. The review demonstrates that innovations in isolation (whether virtual laboratories, AR/VR tools, or flipped classrooms) do not guarantee impact unless grounded in robust pedagogy, supported by teacher expertise, and embedded in coherent curricular structures.

The study contributes to the literature by mapping how diverse innovations converge on shared priorities: addressing misconceptions, enhancing student engagement, and fostering 21st-century skills such as collaboration, critical thinking, and creativity. By situating findings within constructivist and student-centered frameworks, this review clarifies not only the promise of innovation but also the conditions under which it becomes transformative.

The implications of the findings extend across multiple levels. For classroom practice, professional development must empower teachers with the PCK and confidence to integrate emerging tools effectively. For institutions, curriculum reform should incorporate

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interdisciplinary STEM links and sustainability themes while ensuring equitable access to resources. For assessment, validated inventories should be complemented with authentic, technology-enhanced tools capable of capturing higher-order competencies. Together, these directions emphasize systemic alignment rather than piecemeal reform.

This review is not without limitations. Its reliance on Scopus-indexed, English-language sources may exclude important perspectives, particularly from non-English contexts. The predominance of short-term intervention studies and positive reporting biases limits conclusions about scalability and sustainability. Furthermore, the thematic synthesis employed here does not allow for quantitative comparison of effect sizes. These limitations point to future research needs such as longitudinal studies, cross-national analyses, and mixed-methods syntheses that can better capture the complexity of innovation in physics education.

In conclusion, meaningful progress in physics education requires the integration of technological, pedagogical, professional, assessment, and curricular reforms within equity-driven, constructivist frameworks. When aligned systemically, these innovations can cultivate conceptual mastery, scientific literacy, and the problem-solving skills essential for preparing learners to meet the challenges of the twenty-first century.

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