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Physics Learning Technology for Sustainable Development Goals (SDGs): A Literature Study

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Abstract

The integration of technology in physics education has become increasingly important to meet the Sustainable Development Goals (SDGs), particularly in enhancing educational quality, promoting inclusivity, and fostering sustainable practices. This literature study aims to evaluate the effectiveness of various technological tools, including adaptive learning platforms, augmented reality (AR), virtual reality (VR), artificial intelligence (AI), and virtual laboratories, in improving physics education. Utilizing a systematic literature review methodology adhering to PRISMA guidelines, the study analyzed data from a comprehensive selection of peer-reviewed articles sourced from the SCOPUS database, focusing on publications from 2020 to 2024. The results indicate that these technologies significantly enhance student engagement, understanding, and critical thinking skills, thus addressing the limitations of traditional teaching methods. Adaptive learning strategies, when combined with techniques like flipped classrooms and micro-learning, effectively cater to individual student needs, promoting personalized learning experiences. AR and VR provide immersive learning environments, making complex physics concepts more accessible and engaging, while AI tools support lesson planning and problem-solving. Virtual laboratories offer hands-on experimental practice without the constraints of physical lab space. However, the study also identifies challenges such as inadequate teacher training, unequal access to technology, and the need for comprehensive professional development programs. The implications of these findings underscore the necessity of addressing these challenges to fully realize the potential of technology-enhanced education. Recommendations include developing professional development programs, ensuring equitable access to technological resources, and fostering collaborations between educational institutions, industry, and communities.

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INTRODUCTION

The integration of technology in education, particularly in physics learning, has gained significant momentum in recent years, driven by the pressing need to meet the Sustainable Development Goals (SDGs). The 2022 Programme for International Student Assessment (PISA) results underscored an urgent demand for educational reforms that overhaul current curricular frameworks, enhance teacher training, and ensure equitable educational opportunities for sustainable development (Bilad et al., 2024). These reforms are vital for aligning educational practices with global development objectives, thereby fostering a more sustainable future.

Physics, as a fundamental subject in many engineering and scientific disciplines, plays a pivotal role in equipping students with a profound understanding of the natural world and essential problem-solving skills. However, traditional teaching methods in physics often struggle to engage students effectively, leading to a disconnection between theoretical knowledge and practical applications (Castiñeira-Ibáñez et al., 2022). This disconnection can result in students perceiving physics as a subject that lacks relevance to their future careers, thus diminishing their interest and engagement. The introduction of technology in physics education offers a transformative approach to addressing this issue, facilitating the understanding of complex concepts that traditional methods may fail to convey effectively (Faresta et al., 2024).

The Sustainable Development Goals represent both a challenge and an opportunity for future educational practices. Integrating these goals into educational curricula from the outset of students' academic journeys is essential for preparing them to address global challenges. Physics education, given its foundational importance in many engineering programs, is particularly well-suited to incorporate the SDGs (Castiñeira-Ibáñez et al., 2022). For instance, aligning physics education with SDG 4 (Quality Education) ensures that all students receive a high-quality education that promotes lifelong learning opportunities. Similarly, addressing SDG 5 (Gender Equality) within physics education can help bridge the gender gap in STEM fields by encouraging equal participation and representation. Moreover, physics education can contribute significantly to SDG 7 (Affordable and Clean Energy) by providing students with the knowledge and skills needed to innovate in the field of renewable energy. Understanding the principles of energy conversion, transmission, and storage is crucial for developing sustainable energy solutions. Additionally, integrating SDG 9 (Industry, Innovation, and Infrastructure) into physics curricula can inspire students to contribute to building resilient infrastructure and fostering innovation. Finally, promoting SDG 12 (Responsible Consumption and Production) through physics education can encourage students to develop technologies and practices that minimize waste and optimize resource use.

The heterogeneous level of student preparedness, especially in the early years of university, poses a significant limitation. This disparity can hinder the connection between physics and its real-world applications, fostering a lack of interest among students. To mitigate this issue, it is crucial to integrate the SDGs into physics courses, thereby motivating students and enhancing the relevance of the subject. The high sensitivity of current generations to environmental issues underscores the importance of this integration (Castiñeira-Ibáñez et al., 2022).

Higher education institutions play a crucial role in advancing sustainable development through education. By forming partnerships with schools and teacher training centers, these institutions can raise awareness and disseminate sustainable practices within communities (Costa et al., 2023). Information and Communication Technologies (ICT) have been identified as critical mediators in the relationship between innovation and sustainability, positively influencing all dimensions of sustainability (Almawishir & Benlaria, 2024). The adoption of ICT in physics education can thus be instrumental in achieving these goals, offering tools that enhance learning and promote sustainable practices.

The integration of assistive technologies further supports the engagement of individuals with disabilities in educational activities, aligning with the SDGs by ensuring inclusive education for all (Smith et al., 2022). These technologies have demonstrated their relevance in achieving the SDGs, although more research is needed to explore their impact from the perspective of stakeholders in the field of assistive technology provision. Overall, the integration of various technological tools in physics education not only enhances the learning process but also contributes to the broader objectives of sustainable development, ensuring that education remains relevant, inclusive, and effective in addressing global challenges.

The evolution of educational technologies has brought forth significant advancements in teaching methodologies, particularly in the realm of physics education. The use of interactive simulations, virtual laboratories, and AI tools has shown substantial benefits in enhancing student engagement and understanding of physics concepts (Faresta et al., 2024). These innovations offer a more dynamic and interactive approach to learning, fostering critical thinking and problem-solving skills. For instance, the use of PhET simulations in a Problem-Based Learning (PBL) model has been found to significantly enhance students' conceptual understanding in physics (Rianti et al., 2024). This model emphasizes active participation and student-centered learning, which are crucial for developing the skills necessary to address complex real-world problems.

The integration of AI tools in physics education is another noteworthy advancement. AI technologies can support lesson planning, introduce innovative teaching methodologies, and assist in solving complex physics problems, thereby enhancing problem-solving skills and personalized learning experiences (Mustofa et al., 2024). Despite the challenges associated with AI, such as inaccuracies in handling advanced content and the need for human intervention, the potential benefits of AI in education are immense. The strategic use of AI tools can simplify complex concepts, improve comprehension, and provide nuanced feedback, complementing the mentorship provided by human educators (Mustofa et al., 2024).

Furthermore, the use of virtual laboratories has proven to be highly effective in enhancing science process skills among students. For example, the virtual laboratory has been shown to improve students' abilities in forming coherent hypotheses, identifying relevant variables, and interpreting complex data sets (Prihatiningtyas et al., 2024). These skills are essential for scientific inquiry and critical thinking, highlighting the importance of integrating such technological tools into physics education. The interactive and engaging nature of virtual laboratories fosters a deeper understanding of scientific concepts and promotes active learning, which is crucial for developing analytical and scientific thinking skills (Prihatiningtyas et al., 2024).

Interactive Labs technology resources, including Virtual Reality (VR) and Augmented Reality (AR), offer another promising avenue for enhancing physics education. These technologies provide immersive learning experiences that allow students to interact with scientific concepts in novel ways, fostering a deeper understanding and a sense of wonder and curiosity (Verawati & Purwoko, 2024). The use of VR and AR in educational settings has been found to improve students' attitudes towards science, bolster their academic performance, and enhance critical thinking skills. Moreover, these technologies offer a cost-effective, scalable, and safe alternative to traditional laboratory settings, democratizing access to hands-on scientific experimentation (Verawati & Purwoko, 2024).

The problem-based learning, supported by interactive technologies, has also been shown to be highly effective in enhancing physics education. Studies have demonstrated that the PBL model, when integrated with tools like simulations and VR, can significantly improve students' engagement, conceptual understanding, and critical thinking skills (Aliyu et al., 2023; Sarkingobir & Bello, 2024). This approach aligns with contemporary educational practices that prioritize active learning and practical skill development, preparing students for the complexities of the modern scientific landscape. Moreover, the adoption of online self-regulated learning strategies, combined with virtual labs, has been found to enhance critical thinking skills among STEM students. A controlled experimental study demonstrated that students who engaged in interactive virtual labs and self-regulated learning showed significant improvements in critical thinking abilities compared to those who followed traditional educational methods (Ernita et al., 2024). This integrative approach fosters a dynamic and interactive learning environment that promotes deeper engagement with scientific concepts and more effective development of critical thinking skills.

Despite the numerous benefits of integrating technology in physics education, several challenges remain. These include inadequate teacher training, unequal access to technology, and the need for professional development programs to maximize the educational benefits of these innovations (Faresta et al., 2024). Addressing these challenges is crucial for ensuring that the potential of technology-enhanced education is fully realized. For instance, providing comprehensive training for educators on the use of advanced technological tools can enhance their ability to effectively integrate these tools into their teaching practices, thereby improving educational outcomes. Furthermore, ensuring equitable access to technology is essential for promoting inclusive education. Disparities in access to technological resources can exacerbate existing educational inequalities, limiting the benefits of technological advancements to a subset of students. Therefore, efforts must be made to provide all students with access to the necessary technological tools and resources, thereby ensuring that the benefits of technology-enhanced education are widely distributed.

The integration of technology in physics education offers a transformative approach to teaching and learning, aligning educational practices with the broader goals of sustainable development. By incorporating advanced technological tools such as AI, interactive labs, virtual laboratories, and assistive technologies, educators can enhance student engagement, improve conceptual understanding, and foster critical thinking skills. These innovations not only address the limitations of traditional teaching methods but also contribute to the achievement of the SDGs by promoting inclusive, innovative, and sustainable educational practices. As educational technologies continue to evolve, it is essential to address the associated challenges and ensure that these advancements are accessible to all students, thereby maximizing their potential to improve educational outcomes and prepare students for the future.

Research Problems

The integration of technology in physics education, while promising, presents several critical challenges that need to be addressed to maximize its potential and align with the Sustainable Development Goals (SDGs). One of the primary issues is the significant gap in teacher training and professional development. Many educators lack the necessary skills and knowledge to effectively integrate advanced technological tools into their teaching practices (Faresta et al., 2024). This inadequacy can lead to suboptimal implementation of technology, failing to fully engage students or enhance their understanding of complex physics concepts. The need for comprehensive training programs that equip teachers with the requisite skills to utilize these technologies effectively is paramount. Additionally, there is a disparity in access to technological resources across different educational institutions, particularly in developing regions. This inequity exacerbates existing educational inequalities, limiting the benefits of technological advancements to a privileged subset of students and undermining the goal of inclusive education for all.

Moreover, the heterogeneity in student preparedness poses a significant barrier to the effective integration of technology in physics education. Students enter higher education institutions with varying levels of understanding and competency in physics, which can hinder the uniform application of technology-enhanced learning methods (Castiñeira-Ibáñez et al., 2022). This variance necessitates tailored educational approaches that accommodate different learning needs and paces. The lack of personalized learning solutions can lead to disengagement and a perception that physics is irrelevant to students' future careers, further diminishing their interest and participation in the subject. Additionally, the potential inaccuracies and limitations of AI tools in handling advanced content require continuous monitoring and intervention by human educators to ensure educational quality (Mustofa et al., 2024). Addressing these challenges is crucial for realizing the full potential of technology in physics education and ensuring that it contributes effectively to sustainable development by promoting equity, enhancing educational outcomes, and preparing students to tackle global challenges.

Study Objective

Through a systematic literature review, the primary objective of this study is to evaluate the effectiveness of integrating advanced technological tools in physics education to align with the Sustainable Development Goals (SDGs).

Novelty of the Study

The novelty of this study lies in its comprehensive approach to integrating various advanced technologies in physics education and evaluating their collective impact on educational outcomes and sustainable development. Unlike previous studies that have often focused on individual technologies in isolation, this study aims to provide a holistic understanding of how multiple technological tools can be synergistically utilized to enhance physics education. By focusing on the SDGs, this study addresses a critical gap in the literature concerning the role of education in promoting sustainable development. Additionally, this study will provide insights into the practical challenges faced by educators in adopting these technologies, offering recommendations for policy and practice to support their effective implementation.

The integration of technology in education is a rapidly evolving field, and this study seeks to contribute to this dynamic area by exploring the potential of emerging technologies to transform physics education. The findings from this study will not only advance the theoretical understanding of technology-enhanced learning but also provide guidelines for educators and policymakers aiming to align educational practices with global development objectives.

METHODS

Research Design

This study employs a systematic literature review methodology, specifically adhering to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021). The PRISMA framework is renowned for its robustness in ensuring transparency and reproducibility in systematic reviews. By utilizing this method, we aim to provide a comprehensive analysis of the existing literature on Physics Learning Technology and its alignment with Sustainable Development Goals (SDGs). The specific focus is on identifying current research trends, evaluating the effectiveness of various technological interventions in physics education, and understanding the challenges and barriers faced in this domain. PRISMA framework as presented in Figure 1.

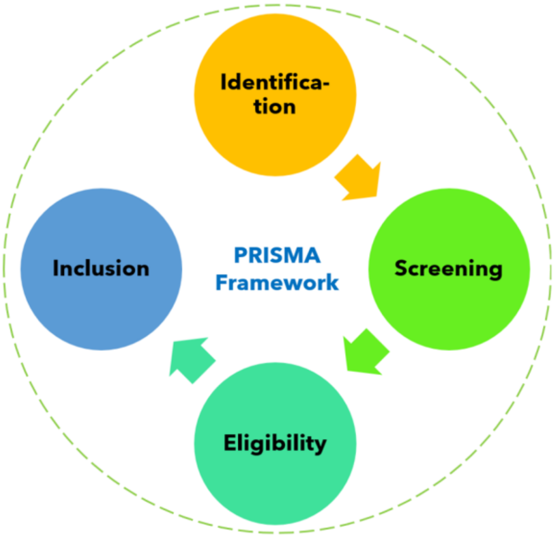

Table 1. The PRISMA framework

Data Sources and Search Strategy

The primary data source for this literature review is the SCOPUS database, chosen for its extensive coverage of peer-reviewed academic literature. The search was conducted using the keyword "Physics Learning Technology," and documents were identified up to July 5, 2024. This keyword was selected to ensure a comprehensive retrieval of relevant articles that discuss technological interventions in physics education. The search strategy was meticulously designed to capture a wide array of studies, including those that might have addressed different aspects of physics learning technology indirectly.

Identification

In the identification phase, all documents retrieved from SCOPUS (https://www.scopus.com/) using the keyword "Physics Learning Technology" were considered [TITLE-ABS-KEY (physics AND learning AND technology)]. The goal was to map out the breadth of research conducted in this area over time. This initial search was broad, capturing studies from all years available in the database until the specified cut-off date. The aim was to establish a comprehensive understanding of the evolution of research in this domain and to identify patterns and trends over time.

Screening

The screening process involved a careful examination of the identified documents [TITLE-ABS-KEY (physics AND learning AND technology) AND PUBYEAR > 2019 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA, "PHYS")) AND (LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))]. Its' to filter out those that did not meet the inclusion criteria. The criteria for this stage were as follows:

1. Document Type: Only journal articles and conference proceedings were included to ensure the quality and relevance of the sources.
2. Language: Documents had to be in English to be included in the review.

3. Subject Area: The focus was restricted to the science domain, specifically physics education.
4. Publication Date: The review was limited to studies published in the last five years to capture the most recent trends and developments in the field.
5. Search Specificity: The keywords had to specifically relate to physics education to ensure the relevance of the articles.

Documents that did not meet these criteria were excluded from further analysis. This rigorous screening process was essential to ensure that only the most pertinent and high-quality studies were included in the subsequent stages of the review.

Eligibility

In the eligibility phase, the remaining documents were evaluated for their relevance to the specific research theme: Technology in Physics Learning. This evaluation was conducted manually by reviewing the abstracts, introductions, and conclusions of the identified studies. Articles that focused explicitly on the use of technology in enhancing physics education and learning were considered eligible. Studies that only tangentially mentioned technology or did not focus on physics learning specifically were excluded. This step ensured that the final selection of articles was directly aligned with the research objectives.

Inclusion

The final phase, inclusion, involved a thorough review of the eligible articles to ensure they met all the predefined criteria. Articles were included based on their direct relevance to the theme of technological interventions in physics education within educational institutions such as schools and universities. Only those studies that specifically discussed the impact of these technologies on teaching and learning in physics, as well as their alignment with SDGs, were included. The inclusion process was critical in narrowing down the pool of studies to those that provided the most insightful and relevant data for the review.

Data Extraction and Analysis

Data from the included studies were extracted systematically, focusing on key information such as author(s), study title, highlights of the study, and the outcomes related to the research objectives. This data extraction process was designed to capture the essence of each study and to facilitate a structured analysis. The extracted data were then analyzed to identify common themes, trends, and gaps in the research. This analysis provided the basis for a comprehensive discussion on the current state of physics learning technology and its implications for sustainable development.

Identifying Authors and Study Highlights

A critical component of the data extraction process involved identifying the authors of the included studies and summarizing the key highlights of their research. This step was essential for attributing the contributions accurately and understanding the focus and findings of each study. By systematically cataloging the authors and their study highlights, we were able to construct a detailed overview of the current research landscape. This overview facilitated a deeper understanding of the main research questions, methodologies, and findings related to physics learning technology and its role in achieving SDGs.

Discussion Based on Study Objectives

The final discussion of the review was structured around the specific objectives of the study. The analysis of the included studies was framed to address each objective, providing a detailed examination of how current research aligns with these goals. For instance, the impact of interactive simulations and virtual laboratories on student engagement and conceptual understanding was evaluated, and the role of AI tools in enhancing problem-solving skills was analyzed. The challenges faced by educators in integrating these advanced technologies into their teaching practices were also critically examined. This structured discussion provided a comprehensive understanding of the current state of research and offered insights into future directions and recommendations for practice and policy.

The PRISMA methodology provided a robust framework for systematically reviewing the literature on physics learning technology and its alignment with SDGs. By meticulously following the stages of identification, screening, eligibility, and inclusion, we ensured that the review was comprehensive, transparent, and reproducible. The insights gained from this review contribute to a deeper understanding of the current trends and challenges in integrating technology into physics education. They highlight the potential of these technologies to enhance educational outcomes and promote sustainable development. The findings underscore the importance of addressing the identified challenges to fully realize the benefits of technology-enhanced learning in physics and to support the achievement of the SDGs.

RESULTS AND DISCUSSION

In the identification phase of this study, a total of 4,766 documents related to physics learning technology were retrieved from the SCOPUS database. These documents span from 1957 to 2024, providing a comprehensive view of the research conducted in this domain over an extended period. The distribution of these documents is illustrated in Figure 2, which categorizes them by year, source, type, and subject area. This extensive collection reflects the growing interest and research efforts dedicated to integrating technology in physics education.

Figure 2 provides a comprehensive overview of the documents retrieved during the identification phase, showcasing a detailed breakdown of the research landscape in physics learning technology from 1957 to 2024. The total of 4.766 documents is distributed across various categories, with significant attention paid to the trends over time, the sources of publication, the type of documents, and the subject areas covered. This broad distribution reflects the expansive and evolving nature of research in this field, highlighting the increasing importance and integration of technology in physics education.

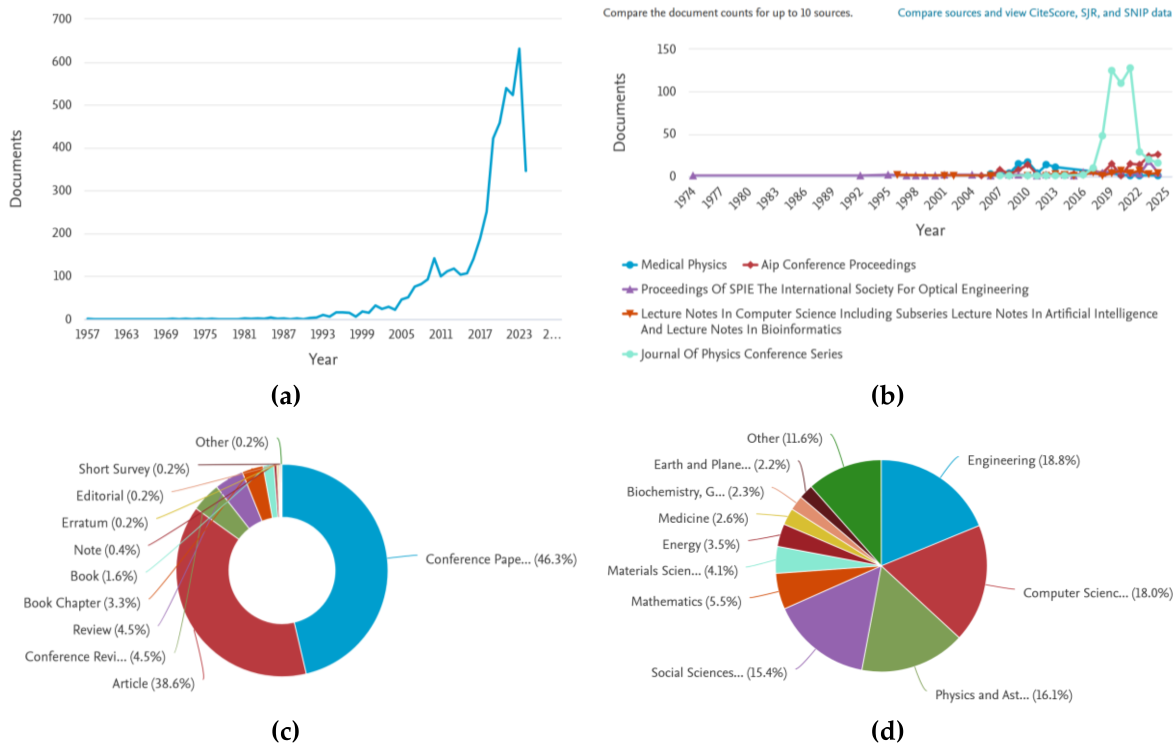

Figure 2. Distribution of documents for all year (from 1957 to 2024); (a) by year, (b) per year by source, (c) by type, and (d) by subject area

The temporal distribution (Figure 2a) indicates a marked increase in the number of documents published in recent years, particularly from 2005 onwards, with a notable peak around 2022. This trend underscores the growing interest and investment in educational technologies in physics, driven by advancements in technology and a greater emphasis on improving educational outcomes. Figure 2b further illustrates this trend by identifying key sources of these publications, such as the "Journal of Physics Conference Series" and "Lecture Notes in Computer Science." These sources are critical platforms for disseminating new research findings and innovations in the field, indicating robust scholarly activity and a supportive publication environment for research in physics education technology.

Figure 2c categorizes the documents by type, revealing that conference papers (46.3%) and journal articles (38.6%) constitute the majority of publications. This distribution suggests a dynamic and rapidly evolving research field, where findings are frequently presented at conferences before being published in peer-reviewed journals. The presence of reviews (4.5%) and book chapters (3.3%) further indicates a depth of scholarship, providing comprehensive overviews and critical analyses of the current state of research. These document types are essential for synthesizing existing knowledge and identifying future research directions, contributing to a well-rounded and mature field of study.

The subject area distribution (Figure 2d) highlights the interdisciplinary nature of research in physics learning technology. While physics and astronomy (16.1%) and engineering (18.8%) are prominently represented, there is also significant overlap with computer science (18.0%), social sciences (15.4%), and mathematics (5.5%). This interdisciplinary approach is crucial for developing and implementing effective technological interventions in physics education, as it draws on insights and methodologies from various fields. The integration of perspectives from social sciences, for instance, can provide valuable insights into the pedagogical and psychological aspects of learning, thereby enhancing the design and efficacy of educational technologies.

These observations collectively emphasize the robust and multidisciplinary efforts to enhance physics education through technological integration, aligning with the broader goals of sustainable development by improving educational access, quality, and outcomes across diverse contexts.

During the screening process, these documents were meticulously examined to filter out those that did not meet the inclusion criteria, which encompassed document type, language, subject area, publication date, and relevance to the specific keywords related to physics education. This rigorous screening reduced the pool to 695 documents published between 2020 and 2024. This focused selection ensured the inclusion of the most recent and pertinent studies, capturing the latest trends and developments in the field.

The subsequent eligibility phase involved a thorough evaluation of the remaining documents to assess their relevance to the specific research theme: the impact of technology in physics learning and its alignment with the Sustainable Development Goals (SDGs). This evaluation emphasized the direct discussion of technological interventions in physics education. Only those studies that explicitly addressed the integration of technology and its effects on teaching and learning in physics were deemed eligible. This step was crucial to ensure that the final selection of documents was directly aligned with the study's objectives.

Ultimately, 16 documents were identified as highly relevant and included in the review (Table 1). These documents form the core of the analysis and discussion, providing a rich source of data on the current state of research in physics learning technology.

Table 1. Studies discussing physics learning technology for SDGs

No	Author(s)	Title	Results	Study highlights
1	(Rincon-Flores et al., 2024)	Improving the learning-teaching process through adaptive learning strategy	The study found that implementing an Adaptive Learning Strategy, combined with didactic techniques like flipped classrooms and micro-learning, significantly improved students' learning and achievement in disciplinary and transversal sub-	The research highlighted the effectiveness of integrating Adaptive Learning Strategies with diverse didactic techniques to enhance the teaching-learning process. It also proposed a successful implementation model for adaptive learning

No	Author(s)	Title	Results	Study highlights
			competencies in physics courses. The integrated approach positively impacted students' engagement and learning outcomes.	designed by the university.
2	(Dawana et al., 2024)	Utilisation of augmented reality technology in physics education: A bibliometric analysis and its impact on Sustainable Development Goals (SDGs)	The bibliometric analysis showed a significant increase in research on Augmented Reality (AR) in physics education over the past decade, with the highest contributions from Indonesia. The study emphasized the potential of AR to enhance higher-order thinking skills and problem-solving in physics.	The research recommended further exploratory studies on AR's potential for sustainable and STEM-based learning. It highlighted the impact of AR on achieving Sustainable Development Goals (SDGs) through improved educational practices.
3	(Koumpouros, 2024)	Revealing the true potential and prospects of augmented reality in education	The systematic review indicated a doubling of publications on AR applications from 2016 to 2020, with most targeting university students. The study found that the majority of AR applications were developed for Android using Unity and Vuforia tools, but faced challenges such as technical problems and limited participant involvement.	The study emphasized the need for effective evaluation methods for AR applications and involvement of all key stakeholders in their development. It proposed key aspects for future research to fully understand AR's potential in education.
4	(Rizki et al., 2024)	Renewable Energy Learning Project in Physics Classroom: Achieving Education for	The project-based learning on the Renewable Energy Learning Project (RELP) improved students' project design,	The research demonstrated the relevance of project-based learning in physics for developing 21st-century skills and

No	Author(s)	Title	Results	Study highlights
		Sustainable Development	communication, and critical thinking skills. The study found that these skills were significantly enhanced through the implementation of RELP in physics lessons.	achieving education for sustainable development. It underscored the importance of integrating renewable energy projects in physics education.
5	(Ayasrah et al., 2024)	Enhancing secondary school students' attitudes toward physics by using computer simulations	The use of computer simulations significantly improved students' attitudes toward physics, particularly in terms of scientific inquiry, enjoyment of science lessons, and career interest in physics. Males showed a greater improvement compared to females.	The study highlighted the efficacy of computer simulations in enhancing students' engagement and attitudes toward physics. It recommended further research and practical applications of computer simulations in science education.
6	(Lucía Asencios-Trujillo et al., 2024)	Virtual Assistance System for Teaching Physics Experiments in University Students	he virtual assistance system for teaching physics experiments demonstrated high efficiency (95.14%) in improving students' experimental practice. The system effectively utilized a dynamic interface to enhance students' learning experience in virtual laboratories.	The research developed a virtual assistance system that prioritized students' time and space, improving their experimental skills in physics. It highlighted the potential of virtual laboratories to overcome traditional educational constraints.
7	(David et al., 2024)	Beyond Digital Twin, Innovative Use of AI/ML Technology from Ideation to Design of Next Generation Electric Drive Systems	The integration of AI and Machine Learning (ML) technologies into Digital Twins significantly enhanced the accuracy and safety of electric propulsion systems. The hybrid	The study provided insights into the application of AI/ML technologies in developing advanced electric drive systems. It showcased the potential of Digital

No	Author(s)	Title	Results	Study highlights
			models achieved a high coefficient of determination (0.9998%) and low root mean square error (0.0063 kwh).	Twins enhanced with AI/ML to improve product development cycles in the mobility industry.
8	(Fatmawati et al., 2024)	Problem-solving skills, collaborative skills and the theme of sustainable energy: Perceptions of students and lecturers in electricity lectures	The study revealed positive perceptions of students and lecturers regarding problem-solving and collaborative skills in electricity lectures. However, 71.1% of students felt that the lectures had not significantly raised awareness about renewable energy technologies.	The research emphasized the need for developing learning models that enhance problem-solving and collaborative skills. It highlighted the importance of integrating sustainable energy topics in physics education to achieve SDGs.
9	(Celestino-Salcedo et al., 2024)	Vodcast embedded with physics education technology simulation in learning projectile motion	The study found that the developed vodcast with embedded PhET simulations was highly rated by experts (overall rating of 4.78) and useful in learning projectile motion. The implementation stage, however, showed a low normalized gain due to distractions during the pandemic.	The research highlighted the development and effectiveness of a vodcast embedded with physics simulations as a supplementary learning material. It addressed the challenge of limited learning resources in the Philippines.
10	(Gulejova, 2024)	Enhancing High School Science Education: Integrating Physics, Technology Innovation, and Sustainable Development	The pilot project Youth@STEM4SF successfully engaged high school students, particularly girls, in physics and STEM fields. The program demonstrated measurable impacts on students' interest and	The research showcased an innovative high school program that contextualized physics and STEM subjects within real-life scenarios related to sustainable development. It

No	Author(s)	Title	Results	Study highlights
			attitudes toward sustainable development.	emphasized the role of education in fostering future societal leaders.
11	(Indahwati et al., 2023)	Integration of independent learning and physics innovation in STEAM-based renewable energy education to improve critical thinking skills in the era of Society 5.0 for Sustainable Development Goals (SDGs) 2030	The literature review showed that integrating Free Learning and Physics Innovation in STEAM-based Renewable Energy Education effectively improved students' critical thinking skills. The approach was relevant to the SDG 2030 agenda.	The study highlighted the importance of integrating contemporary educational approaches with renewable energy topics. It provided guidelines for educators and policymakers to align educational strategies with technological advancements.
12	(Costa et al., 2023)	Physics of Sound to Raise Awareness for Sustainable Development Goals in the Context of STEM Hands-On Activities	The interdisciplinary approach to teaching the physics of sound successfully raised awareness about noise pollution and its consequences. The hands-on activities effectively provided students with 21st-century STEM skills.	The research underscored the importance of interdisciplinary and hands-on activities in raising awareness about environmental issues. It highlighted the role of higher education institutions in promoting sustainable development practices.
13	(Kholiq et al., 2023)	Analysis of the pre-service physics teacher's ability to develop SDGs-oriented multimedia	The study found that pre-service physics teachers demonstrated medium-level abilities in developing SDGs-oriented multimedia. The highest abilities were in video editing and accurate presentation of SDG content.	The research emphasized the need for enhancing pre-service teachers' skills in developing multimedia for physics education. It highlighted the importance of integrating SDGs into educational content to prepare future generations.

No	Author(s)	Title	Results	Study highlights
14	(Nwokolo et al., 2023)	Machine learning and analytical model hybridization to assess the impact of climate change on solar PV energy production	The hybrid model combining machine learning and probabilistic approaches closely matched measured PV energy production, with a high coefficient of determination (0.9998%). The study found minimal adverse impacts of climate change on PV technologies, with CIGS thin film technology being the most resilient.	The research demonstrated the effectiveness of hybrid models in predicting solar PV energy production. It highlighted the resilience of CIGS thin film technology to climate change, providing valuable insights for sustainable energy development.
15	(Samala et al., 2023)	Global Publication Trends in Augmented Reality and Virtual Reality for Learning: The Last Twenty-One Years	The bibliometric analysis showed a rising trend in AR and VR research for learning over the past two decades. The study identified Denmark and India as the leading contributors, with significant influence from specific journals and authors.	The research highlighted the growing interest and influence of AR and VR technologies in education. It recommended further research on AR/VR and Mixed Reality to enhance interactive learning experiences.
16	(Nita et al., 2023)	The challenge and opportunities of quantum literacy for future education and transdisciplinary problem-solving	The study introduced the concept of quantum literacy, using visualization tools to make quantum computing accessible. The puzzle visualization tool effectively helped non-specialists understand complex quantum concepts.	The research addressed the challenge of teaching quantum computing to non-specialists. It proposed quantum literacy as a means to promote inclusive and transdisciplinary education, supporting SDG 4 (Quality Education).

The integration of technology in physics education is pivotal for addressing contemporary educational challenges and aligning with the Sustainable Development Goals

(SDGs). This section provides an in-depth discussion of the results presented in Table 1, highlighting the contributions of each study to the advancement of physics education through technological innovations. It also connects these findings to the broader context of the SDGs, particularly in terms of enhancing quality education, promoting sustainable practices, and fostering inclusive learning environments.

SDG 4: Quality Education

Enhancing Educational Quality through Technology

The integration of technology into physics education has proven to be a significant factor in enhancing the quality of education. Adaptive learning strategies, computer simulations, augmented reality (AR), and virtual reality (VR) are among the technological tools that have shown substantial benefits in improving student engagement, understanding, and retention of complex physics concepts. Rincon-Flores et al. (2024) found that combining adaptive learning strategies with flipped classrooms and micro-learning significantly improved students' learning outcomes and engagement in physics courses. These adaptive platforms were effective in enhancing both disciplinary and transversal sub-competencies, indicating their potential to foster a comprehensive educational experience. The implementation model proposed by the university was successfully evaluated and recommended for broader application, showcasing how adaptive learning can cater to individual student needs and promote personalized learning experiences.

The use of AR and VR technologies further enhances the quality of physics education by providing immersive learning experiences that traditional methods cannot offer. These technologies allow students to visualize and interact with abstract concepts, making them more tangible and easier to understand. For example, AR applications can overlay digital information onto the physical world, helping students see the forces at play in a physics experiment. VR, on the other hand, can create entirely new environments where students can explore and manipulate variables in a controlled setting. These interactive experiences not only make learning more engaging but also improve students' ability to retain and apply knowledge in real-world scenarios.

Personalized and Adaptive Learning

Personalized learning approaches, such as adaptive learning platforms, are designed to meet the individual needs of each student. This approach is essential for addressing diverse learning paces and styles, ensuring that all students, regardless of their starting point, can achieve a high level of understanding and competency in physics. By tailoring educational experiences to individual needs, adaptive learning strategies, as highlighted by Rincon-Flores et al. (2024), promote equity and personalized learning. These platforms allow for continuous assessment and real-time feedback, enabling educators to adjust instructional strategies to better support each student's learning journey.

Adaptive learning platforms utilize algorithms to analyze students' performance and provide personalized content that addresses their specific learning gaps. This continuous feedback loop helps students stay on track and ensures that they are mastering the material before moving on to more advanced topics. Moreover, personalized learning supports the development of self-regulated learning skills, as students take an active role in their education, setting goals, and monitoring their progress. This approach not only enhances academic performance but also fosters a lifelong love of learning, equipping students with the skills they need to succeed in an ever-changing world.

Interactive and Immersive Learning

Technological tools like AR and VR create immersive and interactive learning environments that make abstract physics concepts more tangible and engaging. Dawana et al. (2024) and Koumpouros (2024) explored the potential of AR in education, noting its effectiveness in enhancing higher-order thinking skills and problem-solving abilities. AR applications provide students with a visual and interactive way to understand complex phenomena, thereby deepening their understanding and making learning more enjoyable. These technologies also facilitate experiential learning, allowing students to conduct virtual experiments and simulations that would be difficult or impossible in a traditional classroom setting.

The immersive nature of AR and VR also promotes active learning, where students are actively involved in the learning process rather than passively receiving information. This active engagement helps to reinforce learning and improve retention of complex concepts. For example, VR can simulate a space mission where students must apply physics principles to navigate and solve problems. Such experiences are not only educational but also inspire curiosity and a passion for science. As these technologies become more accessible, they hold the promise of transforming physics education by making it more interactive, engaging, and effective.

Computer Simulations and Virtual Laboratories

Computer simulations and virtual laboratories are other technological advancements that significantly contribute to enhancing the quality of physics education. Ayasrah et al. (2024) demonstrated that the use of computer simulations improved students' attitudes toward scientific inquiry and their enjoyment of science lessons. Simulations like PhET allow students to manipulate variables and observe outcomes in a controlled, virtual environment, fostering a deeper understanding of physical principles. These simulations provide an interactive way to explore concepts that might be too dangerous, expensive, or time-consuming to investigate in a traditional laboratory setting.

Lucía Asencios-Trujillo et al. (2024) highlighted the benefits of virtual laboratories, which provide students with hands-on experience in conducting experiments without the limitations of physical lab space or resources. These virtual labs offer dynamic interactions and detailed feedback, enhancing students' experimental skills and conceptual understanding. Virtual labs can simulate complex experiments that require sophisticated equipment, allowing students to gain practical experience and develop critical thinking skills.

The accessibility and flexibility of virtual labs make them an invaluable resource in modern physics education, ensuring that all students have the opportunity to engage in high-quality experimental learning regardless of their geographic or economic circumstances.

Challenges and Recommendations

While the integration of technology in physics education offers numerous benefits, several challenges need to be addressed to maximize its potential. One of the primary challenges is the need for adequate teacher training. Many educators lack the necessary skills and knowledge to effectively integrate advanced technological tools into their teaching practices (Rincon-Flores et al., 2024). Comprehensive professional development programs are essential to equip teachers with these skills and enhance their ability to utilize technology effectively.

Additionally, there are disparities in access to technological resources across different educational institutions, particularly in developing regions. This inequality can exacerbate existing educational disparities, limiting the benefits of technological advancements to a privileged subset of students. Efforts must be made to ensure equitable access to technology, promoting inclusive education for all students.

The integration of technology in physics education aligns with SDG 4 (Quality Education) by enhancing the quality, accessibility, and inclusiveness of learning experiences. Adaptive learning platforms, computer simulations, AR, and VR have proven effective in engaging students, improving their understanding of complex concepts, and fostering critical thinking skills. However, to fully realize the potential of these technologies, it is crucial to address challenges related to teacher training and equitable access to resources. By doing so, educators can create engaging, inclusive, and effective learning environments that prepare students to tackle global challenges and contribute to sustainable development.

SDG 5: Gender Equality

Addressing Gender Disparities in STEM Education

Achieving gender equality in education, particularly in science, technology, engineering, and mathematics (STEM) fields, is a critical component of SDG 5 (Gender Equality). Several studies have highlighted the importance of addressing gender disparities in STEM education through targeted programs and interventions. For instance, Gulejova (2024) reported on the Youth@STEM4SF program, which aimed to engage high school students, especially girls, in physics and STEM subjects. The program contextualized these disciplines within real-life scenarios related to sustainable development, significantly impacting students' interest and attitudes toward science. By focusing on encouraging girls to pursue STEM, the program addresses gender disparities and promotes a more inclusive educational environment.

Programs like Youth@STEM4SF are crucial in breaking down the stereotypes and biases that often deter girls from pursuing careers in STEM fields. These initiatives not only provide girls with the necessary skills and knowledge but also boost their confidence and interest in

STEM subjects. Additionally, such programs often include mentorship opportunities, where female students can interact with successful women in STEM careers. These role models play a pivotal role in shaping the aspirations of young girls, demonstrating that success in STEM is achievable regardless of gender. By systematically addressing the barriers that girls face in STEM education, these programs contribute significantly to the broader goal of gender equality.

Inclusive Learning Environments

Creating inclusive learning environments is essential for ensuring that all students, regardless of gender, have equal opportunities to excel in physics. Ayasrah et al. (2024) found that computer simulations significantly improved students' attitudes toward physics, with male students showing greater improvement compared to females. This finding underscores the need for educators to develop strategies that address gender differences in educational outcomes and create inclusive learning environments that support all students. For instance, incorporating gender-sensitive pedagogical approaches and providing female role models in STEM can inspire and motivate girls to pursue these fields.

Gender-sensitive pedagogical approaches involve using teaching methods and materials that are free from gender bias and actively promote gender equality. This can include using examples and case studies that feature female scientists and engineers, ensuring that classroom discussions and group activities encourage equal participation from all students, and providing feedback and support tailored to the needs of female students. Additionally, creating a classroom culture that values diversity and inclusivity can help all students feel welcome and supported. Schools and universities can also offer extracurricular activities, such as STEM clubs and competitions, specifically designed to engage and empower female students, providing them with additional opportunities to explore and excel in STEM fields.

Empowering Girls through Technology

Technology plays a crucial role in empowering girls and promoting gender equality in education. Interactive and immersive technologies like AR and VR can make learning more engaging and accessible, helping to bridge the gender gap in STEM education. Dawana et al. (2024) emphasized the potential of AR to enhance higher-order thinking skills and problem-solving abilities, which are critical for success in STEM fields. By providing girls with access to these technologies and supporting their use in educational settings, educators can help level the playing field and encourage more girls to pursue careers in science and technology.

The integration of AR and VR in education offers a unique opportunity to create learning experiences that are both captivating and educational. These technologies can simulate real-world scenarios and experiments, allowing students to explore complex concepts in a hands-on and interactive manner. For girls, who may feel less confident in traditional STEM environments, AR and VR can provide a safe and supportive space to learn and experiment. Moreover, these technologies can be used to highlight the contributions of women in STEM, further inspiring and motivating female students. By leveraging the power of technology, educators can create a more inclusive and empowering educational experience for girls, fostering a new generation of female leaders in STEM.

Challenges and Recommendations

Despite the progress made in promoting gender equality in STEM education, several challenges remain. One of the primary challenges is the persistent gender stereotypes and biases that discourage girls from pursuing STEM subjects. These stereotypes can be perpetuated by societal norms, family expectations, and even classroom dynamics. Addressing these biases requires a multifaceted approach, including awareness campaigns, gender-sensitive curricula, and supportive learning environments that challenge stereotypes and encourage girls to explore their interests in STEM. Additionally, there is a need for more female role models and mentors in STEM fields. The presence of successful women in science and technology can inspire and motivate girls to pursue these careers. Educational institutions and organizations should actively promote female role models and create mentorship programs that connect girls with women in STEM.

Promoting gender equality in physics education and STEM fields is essential for achieving SDG 5 (Gender Equality). By addressing gender disparities through targeted programs, inclusive learning environments, and the use of empowering technologies, educators can ensure that all students, regardless of gender, have equal opportunities to succeed in STEM. While challenges such as gender stereotypes and biases remain, ongoing efforts to raise awareness, provide female role models, and support girls in their educational journeys are crucial for fostering a more inclusive and equitable educational landscape.

SDG 7: Affordable and Clean Energy

Promoting Renewable Energy Education

Integrating renewable energy education into physics curricula is vital for fostering a generation that is aware of and engaged in sustainable energy practices. Educating students about renewable energy sources and sustainability aligns with SDG 7 (Affordable and Clean Energy) and prepares them to address global energy challenges. Rizki et al. (2024) highlighted the effectiveness of the Renewable Energy Learning Project (RELP) in developing students' design, communication, and critical thinking skills. Through project-based learning, students created renewable energy works, such as solar and wind projects, which not only enhanced their understanding of physics concepts but also promoted practical skills relevant to sustainable development. These hands-on projects allow students to apply theoretical knowledge to real-world problems, bridging the gap between classroom learning and practical application.

Project-based learning in renewable energy education not only equips students with technical skills but also fosters a deeper understanding of the environmental impacts of energy choices. By working on projects that involve designing and building renewable energy systems, students gain insight into the complexities and challenges of implementing sustainable energy solutions. This experiential learning approach encourages students to think critically about energy consumption and production, fostering a sense of innovation and creativity. Additionally, these projects often involve collaboration with peers, enhancing teamwork and communication skills essential for future careers in the energy sector. Integrating renewable energy education into physics courses thus plays a crucial role in preparing students to contribute to the global transition towards sustainable energy systems.

Raising Awareness about Sustainable Energy Solutions

Incorporating sustainable energy topics into physics education helps raise awareness about the importance of transitioning to clean energy sources. Fatmawati et al. (2024) emphasized the need to improve awareness and understanding of renewable energy technologies among students. By integrating discussions on sustainable energy into physics lectures, educators can inspire students to consider careers in renewable energy and contribute to the development and adoption of these technologies. This approach not only educates students about sustainable energy solutions but also fosters a sense of responsibility towards environmental stewardship. Educators can use case studies, current events, and emerging technologies in renewable energy to make these topics relevant and engaging for students.

Raising awareness about sustainable energy solutions in physics education also involves highlighting the economic, social, and environmental benefits of renewable energy technologies. By understanding the broader impacts of clean energy, students can appreciate the role of renewable energy in mitigating climate change, reducing pollution, and promoting energy security. This holistic approach helps students recognize the interconnectedness of energy systems and their implications for sustainable development. Furthermore, engaging students in discussions about the policy and regulatory frameworks that support renewable energy can provide them with a comprehensive understanding of the challenges and opportunities in the field. By fostering a well-rounded awareness of sustainable energy solutions, physics education can inspire students to become advocates for clean energy and contribute to a sustainable future.

Technological Innovations in Renewable Energy Education

Technological innovations such as AR, VR, and computer simulations play a significant role in enhancing renewable energy education. These tools provide students with interactive and immersive learning experiences, allowing them to visualize and understand complex energy systems. For example, AR applications can simulate renewable energy projects, demonstrating how solar panels and wind turbines generate electricity. Dawana et al. (2024) and Koumpouros (2024) highlighted the potential of AR in enhancing higher-order thinking skills and problem-solving abilities, which are crucial for understanding and innovating in the field of renewable energy.

Challenges and Recommendations

While integrating renewable energy education into physics curricula offers numerous benefits, several challenges need to be addressed to maximize its impact. One of the primary challenges is the need for adequate teacher training and resources. Educators must be equipped with the knowledge and tools to effectively teach renewable energy concepts and use technological innovations in their classrooms. Professional development programs and access to educational resources are essential for supporting teachers in this endeavor.

Another challenge is ensuring that all students have access to the necessary technological tools and resources. Disparities in access to technology can limit the benefits of renewable energy education to a subset of students, exacerbating existing educational inequalities. Efforts must be made to provide equitable access to these tools, particularly in under-resourced schools and communities.

Promoting renewable energy education in physics aligns with SDG 7 (Affordable and Clean Energy) by fostering awareness, understanding, and innovation in sustainable energy practices. Project-based learning, technological innovations, and raising awareness about sustainable energy solutions are key strategies for achieving this goal. However, addressing challenges related to teacher training and equitable access to resources is crucial for maximizing the impact of renewable energy education. By integrating these approaches, educators can prepare students to contribute to the development and adoption of clean energy technologies, supporting global efforts to transition to a more sustainable energy future.

SDG 9: Industry, Innovation, and Infrastructure

Fostering Innovation through Educational Technology

The integration of AI, Machine Learning (ML), and Digital Twins in physics education and engineering showcases the potential of these technologies to drive innovation and improve educational outcomes. David et al. (2024) explored how AI/ML technologies can enhance the accuracy and safety of electric propulsion systems, demonstrating the application of these technologies in engineering education. Such innovations in educational technology contribute to the development of resilient infrastructure and promote sustainable industrial practices, aligning with SDG 9 (Industry, Innovation, and Infrastructure). By incorporating these advanced technologies into the curriculum, educators can provide students with the skills and knowledge needed to develop innovative solutions to complex engineering problems, thus fostering a culture of continuous improvement and innovation in the industry.

The use of AI and ML in educational settings also facilitates personalized learning experiences, where students can receive tailored instruction and feedback based on their unique learning needs and progress. This approach not only enhances learning outcomes but also prepares students for the rapidly evolving technological landscape of the modern workforce. Digital Twins, which create virtual replicas of physical systems, allow students to experiment and interact with models in a risk-free environment. This hands-on experience with cutting-edge technology helps students understand the practical applications of their theoretical knowledge, bridging the gap between academia and industry. As a result, educational institutions play a pivotal role in driving innovation and ensuring that future engineers and scientists are well-equipped to contribute to the development of sustainable and resilient infrastructure.

Developing Technological Skills for the Future

Educating students with the latest technological tools prepares them for future careers in science, technology, engineering, and mathematics (STEM). The use of virtual laboratories, as discussed by Lucía Asencios-Trujillo et al. (2024), provides students with hands-on experience in a controlled digital environment, enhancing their experimental skills and understanding of physics concepts. These technological skills are essential for the development of innovative solutions to global challenges. By equipping students with the knowledge and skills to use advanced technologies, educators can foster a generation of innovators and problem-solvers who can contribute to the development of sustainable infrastructure and industry. Virtual laboratories offer the flexibility to conduct experiments that may be too costly, dangerous, or logistically challenging to perform in a traditional lab, thus expanding the scope of students' learning experiences.

Furthermore, exposure to advanced technologies in educational settings prepares students to adapt to and thrive in a technologically advanced workforce. As industries increasingly rely on automation, AI, and data analytics, the demand for skilled professionals who can navigate and innovate within these domains continues to grow. By incorporating these technologies into physics and engineering education, institutions can ensure that their graduates possess the necessary skills to meet industry demands and drive future technological advancements. This proactive approach to education not only enhances individual career prospects but also contributes to the broader goal of sustainable economic development, as a skilled workforce is crucial for maintaining competitive and innovative industries.

Interactive and Immersive Learning Environments

Technological tools like AR and VR create immersive and interactive learning environments that make abstract physics concepts more tangible and engaging. Dawana et al. (2024) and Koumpouros (2024) explored the potential of AR in education, noting its effectiveness in enhancing higher-order thinking skills and problem-solving abilities. AR applications provide students with a visual and interactive way to understand complex phenomena, thereby deepening their understanding and making learning more enjoyable. These technologies also facilitate experiential learning, allowing students to conduct virtual experiments and simulations that would be difficult or impossible in a traditional classroom setting. For instance, students can use VR to explore atomic structures or simulate the behavior of particles in different environments, gaining a deeper insight into the subject matter.

The use of AR and VR in education also promotes active learning, where students engage directly with the material, collaborate with peers, and apply their knowledge to solve real-world problems. This approach fosters critical thinking, creativity, and innovation, essential skills for future careers in STEM fields. Interactive learning environments created by AR and VR can simulate real-life scenarios, such as engineering projects or scientific research, providing students with practical experience and preparing them for the challenges of the professional world. By making learning more dynamic and interactive, these technologies not only enhance educational outcomes but also inspire students to pursue careers in STEM, contributing to the development of a skilled and innovative workforce that can drive sustainable industrial growth and infrastructure development.

Challenges and Recommendations

While the integration of technology in physics education offers numerous benefits, several challenges need to be addressed to maximize its potential. One of the primary challenges is the need for adequate teacher training. Many educators lack the necessary skills and knowledge to effectively integrate advanced technological tools into their teaching practices (Rincon-Flores et al., 2024). Comprehensive professional development programs are essential to equip teachers with these skills and enhance their ability to utilize technology effectively.

Additionally, there are disparities in access to technological resources across different educational institutions, particularly in developing regions. This inequality can exacerbate existing educational disparities, limiting the benefits of technological advancements to a privileged subset of students. Efforts must be made to ensure equitable access to technology, promoting inclusive education for all students.

The integration of technology in physics education aligns with SDG 9 (Industry, Innovation, and Infrastructure) by fostering innovation, developing technological skills, and creating interactive learning environments. AI, ML, Digital Twins, AR, and VR are among the technological advancements that contribute to enhancing the quality of education and preparing students for future careers in STEM. However, addressing challenges related to teacher training and equitable access to resources is crucial for maximizing the impact of these technologies. By doing so, educators can create engaging, inclusive, and effective learning environments that prepare students to tackle global challenges and contribute to sustainable development.

SDG 12: Responsible Consumption and Production

Sustainable Educational Practices

The use of digital tools and technologies in education can reduce the need for physical materials, promoting more sustainable consumption practices. By creating virtual learning environments, educational institutions can decrease their environmental footprint while providing high-quality educational experiences. Dawana et al. (2024) and Koumpouros (2024) discussed how AR and VR applications in education can minimize the use of physical resources, supporting responsible consumption and production. These technologies allow students to conduct experiments, visualize concepts, and engage with interactive content without the need for extensive physical materials, reducing waste and conserving resources. For instance, virtual dissections in biology or simulated chemical reactions in physics eliminate the need for physical specimens and chemicals, thus reducing waste and the environmental impact associated with procuring and disposing of these materials.

Moreover, the shift to digital textbooks and online resources can significantly cut down on paper use, contributing to more sustainable educational practices. Digital platforms also provide the flexibility to update and distribute educational materials quickly and efficiently, ensuring that students always have access to the most current information without the need for reprinting physical textbooks. This approach not only conserves natural resources but also reduces the carbon footprint associated with the production and transportation of traditional educational materials. By leveraging these technological advancements, educational institutions can play a pivotal role in promoting responsible consumption and production, aligning with the goals of SDG 12.

Encouraging Sustainable Behaviors

Educational programs that incorporate sustainability themes encourage students to adopt sustainable behaviors in their daily lives. Costa et al. (2023) implemented an interdisciplinary approach to teaching the physics of sound, raising awareness about noise pollution and its health consequences. Such programs highlight the importance of sustainable practices and encourage students to take actions that contribute to environmental preservation. By integrating sustainability education into physics curricula, educators can inspire students to become advocates for responsible consumption and production in their communities. For example, lessons on the environmental impact of energy consumption can lead students to adopt energy-saving habits at home, such as turning off lights and using energy-efficient appliances.

Furthermore, sustainability-focused educational programs can foster a sense of environmental stewardship among students, motivating them to participate in community initiatives and advocacy efforts. By understanding the science behind environmental issues, students can make informed decisions and influence others to adopt sustainable practices. Engaging students in projects like recycling programs or clean-up drives can provide practical experience in environmental conservation and reinforce the importance of sustainable living. These initiatives not only benefit the environment but also cultivate a generation of environmentally conscious individuals committed to promoting sustainability in all aspects of their lives.

Technological Innovations for Sustainability

Technological innovations play a significant role in promoting sustainable consumption and production. For example, AR applications can simulate renewable energy projects, demonstrating how solar panels and wind turbines generate electricity. These simulations provide students with a deeper understanding of sustainable energy solutions and the importance of transitioning to clean energy sources. Dawana et al. (2024) and Koumpouros

(2024) highlighted the potential of AR to enhance higher-order thinking skills and problem-solving abilities, which are crucial for developing innovative solutions to global sustainability challenges. By engaging with these simulations, students can explore the mechanics and benefits of renewable energy technologies, fostering a greater appreciation for sustainable practices and inspiring future careers in green technology.

Additionally, technological innovations such as 3D printing and IoT (Internet of Things) can be integrated into educational settings to promote sustainability. 3D printing can be used to create prototypes and models using sustainable materials, reducing the waste associated with traditional manufacturing processes. IoT devices can help monitor and manage energy use in schools, providing real-time data that can be used to teach students about energy efficiency and conservation. By incorporating these cutting-edge technologies into the curriculum, educators can provide students with hands-on experience in sustainable practices and innovative problem-solving. This approach not only enhances students' technical skills but also instills a mindset geared towards sustainability, preparing them to tackle the environmental challenges of the future.

Challenges and Recommendations

While the integration of technology in education offers numerous benefits, several challenges need to be addressed to maximize its potential for promoting sustainable consumption and production. One of the primary challenges is ensuring that all students have access to the necessary technological tools and resources. Disparities in access to technology can limit the benefits of sustainable educational practices to a subset of students, exacerbating existing educational inequalities. Efforts must be made to provide equitable access to these tools, particularly in under-resourced schools and communities.

Additionally, there is a need for adequate teacher training to effectively integrate sustainability education and technological innovations into physics curricula. Educators must be equipped with the knowledge and skills to teach sustainable practices and use advanced technological tools in their classrooms. Professional development programs and access to educational resources are essential for supporting teachers in this endeavor.

Promoting responsible consumption and production in physics education aligns with SDG 12 (Responsible Consumption and Production) by fostering sustainable educational practices and encouraging students to adopt sustainable behaviors. Technological innovations like AR and VR can reduce the need for physical materials, creating virtual learning environments that minimize waste and conserve resources. Additionally, integrating sustainability education into physics curricula can inspire students to become advocates for responsible consumption and production in their communities. However, addressing challenges related to equitable access to technology and teacher training is crucial for maximizing the impact of these initiatives. By doing so, educators can prepare students to contribute to global sustainability efforts and promote more sustainable consumption and production practices.

SDG 13: Climate Action

Educating for Climate Awareness

Physics education that includes discussions on climate change and sustainability prepares students to address environmental challenges. Educating students about the science behind climate change and the impact of human activities on the environment is essential for fostering a generation that is aware of and engaged in climate action. Gulejova (2024) emphasized the importance of educating future societal leaders about the role of science in sustainable development. By integrating climate awareness into physics education, students are equipped with the knowledge and skills needed to take meaningful action against climate change. This integration can be achieved through curriculum modifications that incorporate climate science, the study of renewable energy technologies, and the examination of policies aimed at reducing greenhouse gas emissions.

Furthermore, physics education can play a crucial role in dispelling myths and misconceptions about climate change. By presenting evidence-based information and fostering critical thinking, educators can help students understand the complexities of climate systems and the urgent need for action. Practical activities, such as experiments that simulate the greenhouse effect or projects that calculate carbon footprints, can make abstract concepts more tangible and relevant to students. These educational practices not only raise awareness but also empower students to become informed advocates for climate action in their communities, thus contributing to a broader societal shift towards sustainability.

Promoting Renewable Energy Education

Integrating renewable energy education into physics curricula is vital for fostering a generation that is aware of and engaged in sustainable energy practices. Educating students about renewable energy sources and sustainability aligns with SDG 13 (Climate Action) and prepares them to address global energy challenges. Rizki et al. (2024) highlighted the effectiveness of the Renewable Energy Learning Project (RELP) in developing students' design, communication, and critical thinking skills. Through project-based learning, students created renewable energy works, such as solar and wind projects, which not only enhanced their understanding of physics concepts but also promoted practical skills relevant to sustainable development. These projects provide hands-on experience, enabling students to explore the feasibility, efficiency, and environmental impact of different renewable energy technologies.

Moreover, renewable energy education can inspire innovation and entrepreneurship among students. By understanding the mechanics and benefits of renewable energy systems, students can envision and develop new technologies that contribute to the transition away from fossil fuels. This education fosters a mindset geared towards problem-solving and sustainability, which is essential for addressing the global climate crisis. Schools and universities that integrate renewable energy projects into their curricula also serve as models for sustainable practices, demonstrating the viability and benefits of clean energy solutions.

This real-world application of physics principles helps students connect their academic learning with pressing global issues, making their education more relevant and impactful.

Raising Awareness about Sustainable Energy Solutions

Incorporating sustainable energy topics into physics education helps raise awareness about the importance of transitioning to clean energy sources. Fatmawati et al. (2024) emphasized the need to improve awareness and understanding of renewable energy technologies among students. By integrating discussions on sustainable energy into physics lectures, educators can inspire students to consider careers in renewable energy and contribute to the development and adoption of these technologies. This approach not only educates students about sustainable energy solutions but also fosters a sense of responsibility towards environmental stewardship. Engaging students with current events and breakthroughs in renewable energy can also stimulate interest and motivate them to explore careers in this critical field.

Raising awareness about sustainable energy solutions in physics education involves not just theoretical knowledge but also practical applications. Educators can incorporate simulations, case studies, and collaborative projects that allow students to explore the potential and limitations of different renewable energy sources. For example, students might design and build their own solar-powered devices or conduct research on the efficiency of wind turbines under varying conditions. These hands-on experiences help students grasp the real-world implications of renewable energy technologies and the challenges involved in their implementation. By fostering a comprehensive understanding of sustainable energy, physics education can play a pivotal role in equipping the next generation with the tools and motivation needed to combat climate change and promote a sustainable future.

Technological Innovations for Climate Action

Technological innovations such as AR, VR, and computer simulations play a significant role in enhancing renewable energy education and promoting climate action. These tools provide students with interactive and immersive learning experiences, allowing them to visualize and understand complex energy systems. For example, AR applications can simulate renewable energy projects, demonstrating how solar panels and wind turbines generate electricity. Dawana et al. (2024) and Koumpouros (2024) highlighted the potential of AR in enhancing higher-order thinking skills and problem-solving abilities, which are crucial for understanding and innovating in the field of renewable energy.

Challenges and Recommendations

While integrating climate awareness and renewable energy education into physics curricula offers numerous benefits, several challenges need to be addressed to maximize its impact. One of the primary challenges is the need for adequate teacher training and resources. Educators must be equipped with the knowledge and tools to effectively teach climate science and renewable energy concepts and use technological innovations in their classrooms.

Professional development programs and access to educational resources are essential for supporting teachers in this endeavor.

Another challenge is ensuring that all students have access to the necessary technological tools and resources. Disparities in access to technology can limit the benefits of climate and renewable energy education to a subset of students, exacerbating existing educational inequalities. Efforts must be made to provide equitable access to these tools, particularly in under-resourced schools and communities.

Promoting climate action through physics education aligns with SDG 13 (Climate Action) by fostering awareness, understanding, and innovation in sustainable energy practices. Project-based learning, technological innovations, and raising awareness about sustainable energy solutions are key strategies for achieving this goal. However, addressing challenges related to teacher training and equitable access to resources is crucial for maximizing the impact of climate and renewable energy education. By integrating these approaches, educators can prepare students to contribute to global climate action efforts and promote a more sustainable future.

SDG 17: Partnerships for the Goals

Collaborative Educational Initiatives

Partnerships between educational institutions, industry, and communities are essential for advancing the SDGs through education. Collaborative initiatives enhance the impact of educational programs and ensure that they are aligned with global sustainability goals. Costa et al. (2023) emphasized the role of higher education institutions in promoting sustainable development through partnerships with schools and teacher training centers. These partnerships facilitate the exchange of knowledge, resources, and best practices, creating a network of support that strengthens educational outcomes and fosters a culture of sustainability. By working together, institutions can pool resources to develop comprehensive educational programs that address local and global challenges, ensuring that students receive a well-rounded education that prepares them for the future.

Additionally, these collaborative efforts often result in the development of innovative educational tools and methodologies. For example, partnerships with industry can lead to the creation of cutting-edge technologies and learning materials that enhance the educational experience. These partnerships also provide students with opportunities for hands-on learning through internships, apprenticeships, and real-world projects. By engaging with industry professionals and community leaders, students gain practical skills and insights that are invaluable in their academic and professional careers. This synergy between education, industry, and community ensures that educational programs are relevant, impactful, and geared towards achieving the Sustainable Development Goals.

Global Research Collaborations

International research collaborations contribute to the development and dissemination of innovative educational practices. Samala et al. (2023) conducted a bibliometric analysis of

AR and VR research, highlighting the influence of international collaborations in advancing educational technology. Such partnerships enable researchers to pool resources, share expertise, and address global challenges collectively. By fostering international collaborations, educational institutions can leverage diverse perspectives and experiences to develop more effective and inclusive educational strategies. These collaborations often result in groundbreaking research that pushes the boundaries of current educational practices, leading to significant advancements in teaching and learning methodologies.

Moreover, global research collaborations can accelerate the pace of innovation and ensure that new educational technologies and practices are quickly disseminated and adopted worldwide. By working together, researchers can identify best practices and successful interventions, adapting them to different cultural and educational contexts. This global approach to research ensures that all students, regardless of their location, can benefit from the latest advancements in educational technology and pedagogy. It also promotes a sense of global citizenship among students and educators, as they become part of a worldwide effort to improve education and achieve the Sustainable Development Goals.

Interdisciplinary Approaches to Education

Interdisciplinary approaches to education, which integrate multiple fields of study, are crucial for addressing complex global challenges. Costa et al. (2023) implemented an interdisciplinary approach to teaching the physics of sound, raising awareness about noise pollution and its health consequences. By incorporating elements of science, technology, engineering, and mathematics (STEM) with environmental education, interdisciplinary programs provide students with a holistic understanding of sustainability issues. These approaches encourage students to think critically and creatively, preparing them to develop innovative solutions to global problems. Interdisciplinary education fosters a more comprehensive understanding of the interconnectedness of various global challenges, promoting a more integrated and effective approach to problem-solving.

Furthermore, interdisciplinary programs often involve collaborative projects that bring together students from different academic backgrounds, fostering a culture of teamwork and mutual respect. These projects allow students to apply their knowledge in real-world contexts, enhancing their learning experience and preparing them for future careers. By working together, students learn to appreciate different perspectives and approaches, which is essential for developing innovative solutions to complex issues. This collaborative and interdisciplinary approach to education not only enriches the learning experience but also ensures that students are well-equipped to contribute to the achievement of the Sustainable Development Goals.

Leveraging Technology for Collaborative Learning

Technological advancements facilitate collaborative learning and enable students to connect with peers, educators, and experts from around the world. Virtual laboratories, online simulations, and interactive platforms create opportunities for students to engage in collaborative projects and discussions, regardless of geographical barriers. Lucía Asencios-Trujillo et al. (2024) highlighted the benefits of virtual laboratories, which provide students with hands-on experience in a controlled digital environment. These technologies promote collaborative learning by allowing students to work together on experiments and problem-solving activities, fostering a sense of community and shared purpose. Virtual laboratories also allow for real-time feedback and interaction, enhancing the learning experience and ensuring that students can learn from their mistakes and successes.

In addition, online platforms and digital tools enable educators to create collaborative learning environments that are dynamic and engaging. These platforms can host virtual classrooms, discussion forums, and collaborative projects, allowing students to work together and learn from each other. This connectivity also extends to partnerships with international educational institutions, enabling students to participate in global learning initiatives and cultural exchanges. By leveraging technology, educators can create a more inclusive and interactive learning environment that breaks down geographical barriers and fosters a global community of learners committed to achieving the Sustainable Development Goals.

Challenges and Recommendations

While partnerships and collaborations offer numerous benefits, several challenges need to be addressed to maximize their impact. One of the primary challenges is ensuring effective communication and coordination among partners. Collaborative initiatives often involve multiple stakeholders with different goals, priorities, and resources. Clear communication, mutual understanding, and well-defined roles and responsibilities are essential for successful partnerships.

Another challenge is the need for sustained commitment and support from all partners. Collaborative initiatives require long-term investment in terms of time, resources, and effort. Ensuring that all partners are committed to the shared goals and actively contribute to the partnership is crucial for achieving lasting impact.

Promoting partnerships and collaborations in physics education aligns with SDG 17 (Partnerships for the Goals) by fostering collective action towards sustainable development. Collaborative educational initiatives, global research collaborations, interdisciplinary approaches, and leveraging technology for collaborative learning are key strategies for achieving this goal. However, addressing challenges related to communication, coordination, and sustained commitment is crucial for maximizing the impact of these partnerships. By fostering a culture of collaboration and shared purpose, educators can enhance the quality of education, promote sustainability, and contribute to the achievement of the SDGs.

CONCLUSION

The integration of technology in physics education is pivotal for addressing contemporary educational challenges and aligning with the Sustainable Development Goals (SDGs). The studies presented in Table 1 demonstrate how technological innovations in education can enhance the quality of learning, promote gender equality, raise awareness about sustainable energy, foster innovation, and support climate action. By leveraging these technologies, educators can create engaging, inclusive, and effective learning environments that prepare students to tackle global challenges and contribute to sustainable development. The findings underscore the importance of ongoing efforts to integrate technology in education and develop strategies that align educational practices with the broader goals of the SDGs. Addressing challenges related to teacher training, equitable access to resources, and effective partnerships is crucial for maximizing the impact of these initiatives and ensuring that all students have the opportunity to succeed in a rapidly changing world.

LIMITATION

Despite the promising advancements in integrating technology into physics education, this study has several limitations that must be acknowledged. One significant limitation is the disparity in access to advanced technological tools and resources across different educational institutions, particularly in developing regions. This inequity exacerbates existing educational inequalities, limiting the benefits of technological advancements to a subset of students and undermining the goal of inclusive education for all. Additionally, there is a notable gap in teacher training and professional development, as many educators lack the necessary skills and knowledge to effectively integrate these technologies into their teaching practices. This inadequacy can lead to suboptimal implementation of technology, failing to fully engage students or enhance their understanding of complex physics concepts. Furthermore, the heterogeneity in student preparedness poses a significant barrier to the uniform application of technology-enhanced learning methods, necessitating tailored educational approaches that accommodate different learning needs and paces. Finally, the study primarily relies on literature reviews and meta-analyses, which may not capture the full spectrum of practical challenges and contextual nuances faced in diverse educational settings.

RECOMMENDATION

To address the limitations identified in this study and maximize the potential of technology-enhanced physics education, several recommendations are proposed. First, it is crucial to develop comprehensive professional development programs that equip educators with the requisite skills to utilize advanced technological tools effectively. These programs should focus on both the pedagogical and technical aspects of integrating technology into physics education. Second, efforts must be made to ensure equitable access to technological resources across all educational institutions, particularly in under-resourced areas. This could involve governmental and non-governmental initiatives to provide necessary funding, infrastructure, and support. Third, personalized learning solutions should be developed to cater to the diverse learning needs and paces of students, ensuring that all learners can benefit from technology-enhanced education. Additionally, ongoing research and pilot programs should be encouraged to explore innovative applications of technology in physics education and assess their impact in real-world settings. Finally, fostering collaborations between educational institutions, industry, and communities can enhance the exchange of knowledge and resources, supporting the development and dissemination of effective technological interventions in physics education. By implementing these recommendations, stakeholders can work towards creating an inclusive, innovative, and sustainable educational environment that aligns with the Sustainable Development Goals (SDGs).

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The authors have sufficiently contributed to the study, and have read and agreed to the published version of the manuscript.

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Conflict of interests
The authors declare no conflict of interest.

REFERENCES

Aliyu, H., Ebikabowei, M., & Kola, A. J. (2023). Problem-Based Learning in Remote Learning Scenario Utilizing Climate Change Virtual Reality Video in Mobile Application to Train Critical Thinking. *International Journal of Essential Competencies in Education*, *2*(2), 144–159. https://doi.org/10.36312/ijece.v2i2.1612

Almawishir, N. F. S., & Benlaria, H. (2024). Innovation and dimensions of sustainable development: Mediating role of ICTs. *Cogent Business & Management*, *11*(1), 2336306. https://doi.org/10.1080/23311975.2024.2336306

Ayasrah, F. T. M., Alarabi, K., Mansouri, M. A., Fattah, H. A. A., & Al-Said, K. (2024). Enhancing secondary school students' attitudes toward physics by using computer simulations. *International Journal of Data and Network Science*, *8*(1), 369–380. https://doi.org/10.5267/j.ijdns.2023.9.017

Bilad, M. R., Zubaidah, S., & Prayogi, S. (2024). Addressing the PISA 2022 Results: A Call for Reinvigorating Indonesia's Education System. *International Journal of Essential Competencies in Education*, *3*(1), 1–12. https://doi.org/10.36312/ijece.v3i1.1935

Castiñeira-Ibáñez, S., Tarrazó-Serrano, D., Gasque, M., Rubio, C., & Uris, A. (2022). *Sustainable development goals and their implementation in physics*. EDULEARN22 Proceedings, 9378–9383. https://doi.org/10.21125/edulearn.2022.2263

Celestino-Salcedo, R. K. M., Malayao, Jr., S. O., Salic-Hairulla, M. A., Castro, E. J., & Mordeno, I. C. V. (2024). Vodcast embedded with physics education technology simulation in learning projectile motion. *Journal of Education and Learning (EduLearn)*, *18*(3), 1039–1047. https://doi.org/10.11591/edulearn.v18i3.21434

Costa, M. C., Ferreira, C. A. F., & Pinho, H. J. O. (2023). Physics of Sound to Raise Awareness for Sustainable Development Goals in the Context of STEM Hands-On Activities. *Sustainability (Switzerland)*, *15*(4). Scopus. https://doi.org/10.3390/su15043676

David, P., Oueslati, S., Bourniche, E., & Nanjundaswamy, H. (2024). *Beyond Digital Twin, Innovative Use of AI/ML Technology from Ideation to Design of Next Generation Electric Drive Systems*. SAE Technical Papers. Scopus. https://doi.org/10.4271/2024-01-2862

Dawana, I. R., Prahani, B. K., Hariyono, E., Ghofur, M. A., Wibowo, F. C., & Bunyamin, M. A. H. (2024). Utilisation of augmented reality technology in physics education: A bibliometric analysis and its impact on Sustainable Development Goals (SDGs). *E3S Web of Conferences*, *513*, 04006. https://doi.org/10.1051/e3sconf/202451304006

Ernita, N., Bahtiar, B., Zulkarnaen, Z., Mustofa, H. A., & Faresta, R. A. (2024). Online Self-Regulated Learning Assisted by Virtual Labs to Train STEM Student's Critical Thinking Skills. *International Journal of Essential Competencies in Education*, *3*(1), 28–46. https://doi.org/10.36312/ijece.v3i1.1917

Faresta, R. A., Nicholas, T. Z. S. B., Chi, Y., Sinambela, I. A. N., & Mopoliu, A. Z. (2024). Utilization of Technology in Physics Education: A Literature Review and Implications for the Future Physics Learning. *Lensa: Jurnal Kependidikan Fisika*, *12*(1), 1. https://doi.org/10.33394/j-lkf.v12i1.11676

Fatmawati, S., Rahardjo, S. B., Harjana, & E., E. S. (2024). *Problem-solving skills, collaborative skills and the theme of sustainable energy: Perceptions of students and lecturers in electricity lectures*. 020031. https://doi.org/10.1063/5.0200935

Gulejova, B. B. (2024). *Enhancing High School Science Education: Integrating Physics, Technology Innovation, and Sustainable Development*. *449*. Scopus.

Indahwati, S. D., Rachmadiarti, F., Hariyono, E., Prahani, B. K., Wibowo, F. C., Bunyamin, M. A. H., & Satriawan, M. (2023). Integration of independent learning and physics innovation in STEAM-based renewable energy education to improve critical thinking skills in the era of Society 5.0 for Sustainable Development Goals (SDGs) 2030. *E3S Web of Conferences*, *450*, 01010. https://doi.org/10.1051/e3sconf/202345001010

Kholiq, A., Sucahyo, I., Anggaryani, M., Satriawan, M., & Habibbulloh, M. (2023). Analysis of the pre-service physics teacher's ability to develop SDGs-oriented multimedia. *E3S Web of Conferences*, *450*, 01008. https://doi.org/10.1051/e3sconf/202345001008

Koumpouros, Y. (2024). Revealing the true potential and prospects of augmented reality in education. *Smart Learning Environments*, *11*(1), 2. https://doi.org/10.1186/s40561-023-00288-0

Lucía Asencios-Trujillo, Lida Asencios-Trujillo, Carlos LaRosa-Longobardi, Djamila Gallegos-Espinoza, Livia Piñas-Rivera, & Rosa Perez-Siguas. (2024). Virtual Assistance System for Teaching Physics Experiments in University Students. *Journal of Advanced Research in*

Applied Sciences and Engineering Technology, *40*(1), 109–117. https://doi.org/10.37934/araset.40.1.109117

Mustofa, H. A., Bilad, M. R., & Grendis, N. W. B. (2024). Utilizing AI for Physics Problem Solving: A Literature Review and ChatGPT Experience. *Lensa: Jurnal Kependidikan Fisika*, *12*(1), 78. https://doi.org/10.33394/j-lkf.v12i1.11748

Nita, L., Mazzoli Smith, L., Chancellor, N., & Cramman, H. (2023). The challenge and opportunities of quantum literacy for future education and transdisciplinary problem-solving. *Research in Science & Technological Education*, *41*(2), 564–580. https://doi.org/10.1080/02635143.2021.1920905

Nwokolo, S. C., Obiwulu, A. U., & Ogbulezie, J. C. (2023). Machine learning and analytical model hybridization to assess the impact of climate change on solar PV energy production. *Physics and Chemistry of the Earth, Parts A/B/C*, *130*, 103389. https://doi.org/10.1016/j.pce.2023.103389

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Systematic Reviews*, *10*(1), 89. https://doi.org/10.1186/s13643-021-01626-4

Prihatiningtyas, S., Haryono, H. E., & Putra, I. A. (2024). Digitization of Learning Through Virtual Laboratory in Assessing Students' Science Process Skills on Mechanical Wave Material. *Lensa: Jurnal Kependidikan Fisika*, *12*(1), 44. https://doi.org/10.33394/j-lkf.v12i1.11534

Rianti, R., Gunawan, G., Verawati, N. N. S. P., & Taufik, M. (2024). The Effect of Problem Based Learning Model Assisted by PhET Simulation on Understanding Physics Concepts. *Lensa: Jurnal Kependidikan Fisika*, *12*(1), 28. https://doi.org/10.33394/j-lkf.v12i1.8783

Rincon-Flores, E. G., Castano, L., Guerrero Solis, S. L., Olmos Lopez, O., Rodríguez Hernández, C. F., Castillo Lara, L. A., & Aldape Valdés, L. P. (2024). Improving the learning-teaching process through adaptive learning strategy. *Smart Learning Environments*, *11*(1), 27. https://doi.org/10.1186/s40561-024-00314-9

Rizki, I. A., Hariyono, E., Suprapto, N., Dawana, I. R., & Shobah, N. (2024). Renewable Energy Learning Project in Physics Classroom: Achieving Education for Sustainable Development. *TEM Journal*, 1452–1460. https://doi.org/10.18421/TEM132-59

Samala, A. D., Daineko, Y., Indarta, Y., Nando, Y. A., Anwar, M., & Jaya, P. (2023). Global Publication Trends in Augmented Reality and Virtual Reality for Learning: The Last

Twenty-One Years. *International Journal of Engineering Pedagogy*, *13*(2), 109–128. Scopus. https://doi.org/10.3991/ijep.v13i2.35965

Sarkingobir, Y., & Bello, A. (2024). Helping Students Become Proficient Physics Problem Solvers Through Problem-Based Learning. *International Journal of Essential Competencies in Education*, *3*(1), 13–27. https://doi.org/10.36312/ijece.v3i1.1813

Smith, E. M., Ebuenyi, I. D., Kafumba, J. A., Jamali-Phiri, M., Munthali, A., & MacLachlan, M. (2022). Relevance of assistive technology and the sustainable development goals to stakeholder organizations in Malawi. *Global Health Action*, *15*(1), 2133381. https://doi.org/10.1080/16549716.2022.2133381

Verawati, N. N. S. P., & Purwoko, A. A. (2024). Literature Review on the Use of Interactive Labs Technology in The Context of Science Education. *International Journal of Ethnoscience and Technology in Education*, *1*(1), 76. https://doi.org/10.33394/ijete.v1i1.12154