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Integrating Earthquake Technologies into Physics Learning for Education for Sustainable Development: A Systematic Literature Review

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ABSTRACT

Objective: *This study aims to synthesize current research on integrating earthquake-related technologies into physics education within the framework of Education for Sustainable Development (ESD). The objective is to examine how these technologies contribute to students' scientific literacy, critical thinking, and disaster preparedness, while also aligning with sustainability goals such as SDG 4 (Quality Education) and SDG 11 (Sustainable Cities and Communities).* ***Method:*** *A Systematic Literature Review (SLR) was conducted using the PRISMA 2020 framework. A total of 546 records were identified from databases, including Scopus, Web of Science, ERIC, and ScienceDirect, with 38 studies meeting the inclusion criteria after screening. Data were analyzed thematically and categorized into technological approaches, pedagogical strategies, and reported learning outcomes.* ***Results:*** *The findings demonstrate that earthquake technologies, including VR/AR simulations, shake tables, and real-time sensors, have a positive impact on student engagement, conceptual understanding, and disaster risk awareness. Pedagogical integration through inquiry-based, project-based, gamification, and problem-solving approaches enhances collaboration, critical thinking, and contextual application of physics concepts. However, challenges remain in terms of limited access to technology, insufficient teacher training, and the lack of longitudinal evidence.* ***Novelty:*** *Unlike previous studies that treated disaster education and physics pedagogy separately, this review bridges both domains under the ESD agenda. It highlights the transformative role of physics classrooms as laboratories for resilience and sustainability, providing a comprehensive framework for integrating disaster-related technologies into science education.*

INTRODUCTION

Physics education has long been envisioned as a platform not only for developing students' conceptual mastery of natural laws but also for cultivating their capacity to apply scientific knowledge in addressing real-world problems. Within the global framework of Education for Sustainable Development (ESD), physics learning is expected to go beyond abstract derivations and formulas by nurturing scientific literacy, critical thinking, and disaster preparedness. The United Nations Educational, Scientific, and Cultural Organization (UNESCO) emphasizes that education must equip learners with the competencies to build a sustainable and resilient society, particularly in regions vulnerable to natural hazards such as earthquakes (UNESCO, 2020; Fekete, 2021; O'Keeffe et al., 2023). Ideally, physics classrooms can function as laboratories for resilience, where concepts like waves, resonance, and energy transfer are directly linked to earthquake risk reduction and mitigation strategies (Malavoloneque & Costa, 2021; O'Reilly et al., 2020). This expectation aligns with the Sustainable Development Goals (SDG 4: Quality Education) and SDG 11 (Sustainable Cities and Communities), which explicitly highlight the integration of sustainability into learning as a critical agenda for disaster-prone nations (Hu et al., 2022; Ji et al., 2023).

Despite these aspirations, the integration of earthquake-related technologies into physics classrooms remains sporadic and underdeveloped. Studies in disaster-prone countries such as Indonesia, Japan, and Nepal reveal that physics teaching is still dominated by decontextualized problem-solving exercises that fail to connect with local disaster realities (Hidayat et al., 2017; Karimzadeh et al., 2020; Suwito et al., 2022). A recent study in Indonesia showed that elementary and secondary students who had experienced earthquake drills were still unable to explain the physics of seismic waves or the engineering principles behind safe building structures (Rachman et al., 2023; Putri et al., 2024). Similarly, Masroni and Elsafitra (2024) demonstrated that while earthquake simulation videos increased short-term awareness, students often lacked deeper conceptual transfer when such simulations were not accompanied by structured physics instruction (Shaw et al., 2021; Wang et al., 2023). This reality highlights a persistent mismatch between students' everyday exposure to seismic risks and the limited educational scaffolding provided in the physics curriculum (Nyarko et al., 2024).

The disjuncture between educational expectations and current practice forms a significant gap in sustainable science education. While governments and international agencies encourage disaster education as part of sustainable development initiatives, physics instruction has not yet systematically embraced this directive. A bibliometric analysis of disaster-related STEM education revealed that most research focuses on emergency management training and social awareness, with fewer studies explicitly connecting disaster risk reduction with disciplinary science learning (Hu et al., 2022; Rahman et al., 2023; O'Keeffe et al., 2023). Moreover, when earthquake topics are included, they are often treated as supplementary or extracurricular activities, rather than as integral parts of physics learning outcomes (Partini et al., 2022; Adriaenssens et al., 2024). This gap prevents students from fully appreciating how scientific knowledge intersects with resilience building and limits the transformative role that physics education can play in sustainability agendas (O'Reilly et al., 2020).

Two interrelated problems emerge from this situation. First, curricula and textbooks often fail to provide teachers with structured models for integrating earthquake technologies into physics lessons. As a result, teachers rely on traditional teaching strategies that emphasize content coverage over contextual application (Hidayat et al., 2017; Nyarko et al., 2024). Second, there is a scarcity of empirical research that evaluates the effectiveness of embedding earthquake technologies such as shake tables, structural models, or seismic sensors into physics pedagogy with ESD goals in mind (Aydinoglu & Ulusoy, 2020; Danciu et al., 2021; Bianchi-Berger et al., 2025; Papanikolaou et al., 2025). Without addressing these issues, physics education risks perpetuating a knowledge–action gap, where students can solve textbook problems but remain illprepared to apply physics in disaster preparedness and mitigation contexts (Hidayat et al., 2017; Shaw et al., 2021).

Nevertheless, several promising initiatives demonstrate the potential of technology-enhanced earthquake education. For instance, Vidak et al. (2023) reviewed the use of augmented reality (AR) in physics instruction, highlighting its effectiveness in helping students visualize complex concepts, such as wave propagation and building resonance during earthquakes (Kapp et al., 2020; Yoon et al., 2021; Zhang et al., 2025). Rajabi et al. (2022) employed immersive virtual environments to simulate earthquake scenarios, reporting improved student engagement and reduced anxiety regarding disaster preparedness (Khan et al., 2020; Guo et al., 2023). Similarly, hands-on approaches, such as using shake tables to test building models, have been shown to effectively bridge theory and practice, while also fostering problem-solving and design skills (Lestari et al., 2021; Bianchi-Berger et al., 2025). These positive cases suggest that integrating earthquake technologies is not only feasible but also pedagogically robust when aligned with physics learning objectives (Rachman et al., 2023).

Despite these advances, significant barriers hinder widespread implementation. High-tech solutions, such as AR and VR, require substantial financial investment, stable infrastructure, and digital teacher competence, which are often lacking in developing regions (Kapp et al., 2020; Yoon et al., 2021; Vidak et al., 2023). Even when resources are available, challenges related to cognitive overload, limited curricular alignment, and teacher preparedness reduce the long-term effectiveness of these innovations (Rajabi et al., 2022; Zhang et al., 2025). Moreover, many interventions remain pilot projects without sustainable institutional adoption (O'Keeffe et al., 2023). Consequently, while the promise of technology-supported earthquake education is clear, current practices still reveal uneven accessibility and inconsistent quality, underscoring the need for systematic evaluation and integration frameworks (O'Reilly et al., 2020; Hu et al., 2022).

In light of these opportunities and constraints, this article presents a Systematic Literature Review (SLR) that aims to synthesize the current state of research on integrating earthquake technologies into physics education within the ESD framework. This review seeks to: (1) map global trends in the adoption of earthquake-related technologies in physics classrooms, (2) analyze their contribution to developing ESD-related competencies such as resilience, problem-solving, and critical thinking, and (3) identify gaps and challenges that need to be addressed in future research and practice (Hu et al., 2022; Ji et al., 2023). By providing an evidence-based synthesis, this article aims to offer practical and theoretical insights for educators, policymakers, and curriculum developers (Fekete, 2021).

The novelty of this work lies in its comprehensive and interdisciplinary perspective. Unlike previous reviews that separately examined disaster education or physics pedagogy, this study explicitly bridges earthquake technologies, physics education, and ESD into a unified framework. It highlights both positive practices that can be strengthened and weaknesses that must be addressed to optimize learning for sustainable development (O'Reilly et al., 2020; Malavoloneque & Costa, 2021). Furthermore, by situating physics education within the broader discourse of resilience and sustainability, this article contributes to a new understanding of how science classrooms can serve as catalysts for disaster risk reduction and sustainable societal transformation (Hu et al., 2022; O'Keeffe et al., 2023).

RESEARCH METHOD

This study employed a Systematic Literature Review (SLR) guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework (Page et al., 2021; Haddaway et al., 2022). The SLR approach was chosen to synthesize existing evidence, identify research trends, and highlight gaps regarding the integration of earthquake technologies into physics education for Education for Sustainable Development (ESD) (O'Keeffe et al., 2023; Rahman et al., 2023). The literature search was conducted systematically across five major electronic databases: Scopus, Web of Science, ERIC, ScienceDirect, and Google Scholar. To ensure comprehensive coverage, additional hand-searching of relevant conference proceedings and grey literature was also performed (Grant & Booth, 2018). The search was limited to studies published between 2015 and 2025, considering the rapid advancement of disaster-related technologies and their integration into education during the last decade (Hu et al., 2022; Ji et al., 2023).

The following Boolean string was applied with minor adjustments depending on database requirements: ("earthquake technology" OR "earthquake simulation" OR "seismic learning" OR "shake table" OR "disaster technology") AND ("physics education" OR "physics learning" OR "science education") AND ("Education for Sustainable Development" OR "ESD" OR "sustainability" OR "disaster risk reduction") (Xiao & Watson, 2019). The inclusion criteria of this review encompassed empirical studies, systematic reviews, or case studies that specifically addressed earthquake-related technologies in the context of physics or science education. Only articles that explicitly connected their work to Education for Sustainable Development (ESD), sustainability, or disaster preparedness were considered (Fekete, 2021; Tran et al., 2022). Furthermore, to ensure academic rigor, the review was limited to peer-reviewed journal articles, conference proceedings, and book chapters published in the English language. Conversely, several categories of studies were excluded. Articles that focused solely on engineering or seismology without any educational relevance were omitted, as were those unrelated to physics or science learning. Non-peer-reviewed sources such as blogs, reports, or other informal publications were also excluded. Additionally, duplicate records retrieved from multiple databases were removed during the screening stage to prevent redundancy (Hiebl, 2021).

The screening process followed four steps using PRISMA guidelines: (1) identification, (2) screening, (3) eligibility, and (4) inclusion. After removing duplicates, titles and abstracts were screened based on inclusion criteria. Full-text assessments were then carried out for potentially relevant studies. The final selection was reached through consensus between two independent reviewers, with disagreements resolved through discussion (Snyder, 2019; Moher et al., 2015).

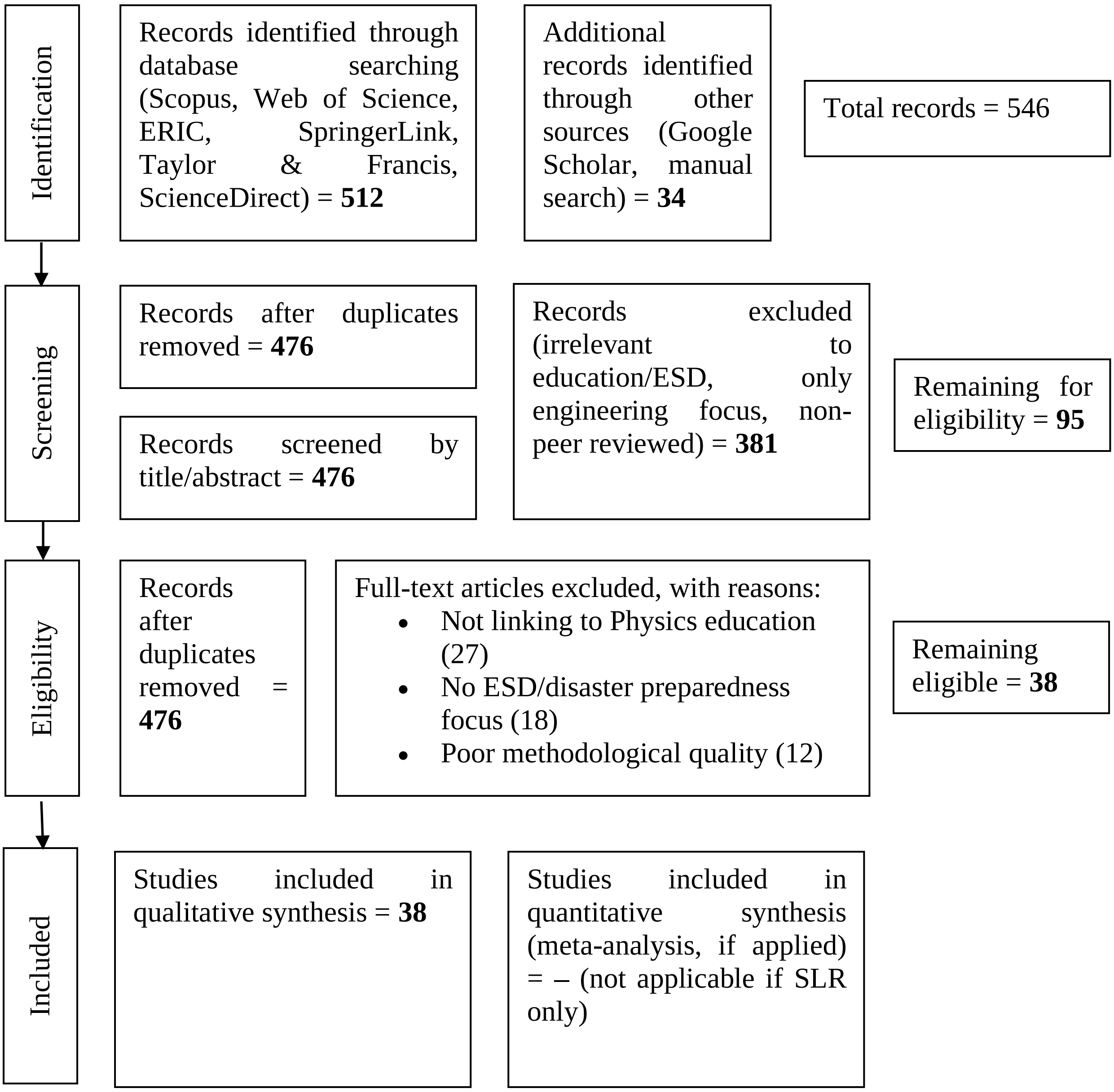

Figure 1. PRISMA flow diagram

A total of 546 records were identified through database searches. After removing duplicates, 476 records remained. Following title and abstract screening, 95 full-text articles were assessed for eligibility. Finally, 38 studies met the inclusion criteria and were included in the qualitative synthesis. A structured data extraction form was developed to collect essential information: authors, year, country, educational level, type of earthquake technology, instructional approach, measured outcomes, and ESD competencies addressed (Booth et al., 2021). To ensure reliability, extraction was performed independently by two researchers and cross-checked for consistency (Hiebl, 2021). A quality appraisal of the selected studies was conducted using the Mixed

Methods Appraisal Tool (MMAT) (Hong et al., 2018; Souto et al., 2022), which enabled an assessment across qualitative, quantitative, and mixed-methods designs.

Data were synthesized using a narrative thematic analysis supported by descriptive statistics (e.g., frequency of technology type, education level, geographical distribution) (Thomas & Harden, 2008; Braun & Clarke, 2019). Studies were categorized into thematic clusters, such as (1) simulation-based earthquake learning (e.g., shake tables, VR/AR) (Guo et al., 2023; Vidak et al., 2023), (2) integration of local wisdom and contextual disaster knowledge (Shaw et al., 2021; Kawakami et al., 2021), and (3) technology-enhanced ESD competencies (Malavoloneque & Costa, 2021; Tran et al., 2022). Emerging trends, challenges, and research gaps were identified to provide evidence-based insights for future directions (Snyder, 2019; O'Keeffe et al., 2023).

RESULTS AND DISCUSSION

Results

Descriptive analysis of selected studies

A total of 38 articles were included after applying the PRISMA selection process, representing a relatively focused body of literature on earthquake-related technologies in physics education for Education for Sustainable Development (ESD). The publication trend shows a noticeable growth after 2015, which aligns with the increasing global awareness of ESD, STEM integration, and disaster preparedness initiatives. Most of the reviewed studies were published as peer-reviewed journal articles. At the same time, a smaller proportion appeared in conference proceedings and book chapters, indicating that this field is progressively gaining stronger academic recognition. Geographically, research is predominantly concentrated in the Asia-Pacific region, particularly in earthquake-prone countries such as Indonesia, Japan, and the Philippines. This regional emphasis highlights the urgent need to integrate earthquake-related knowledge into physics and science education as part of disaster risk reduction and sustainable development initiatives.

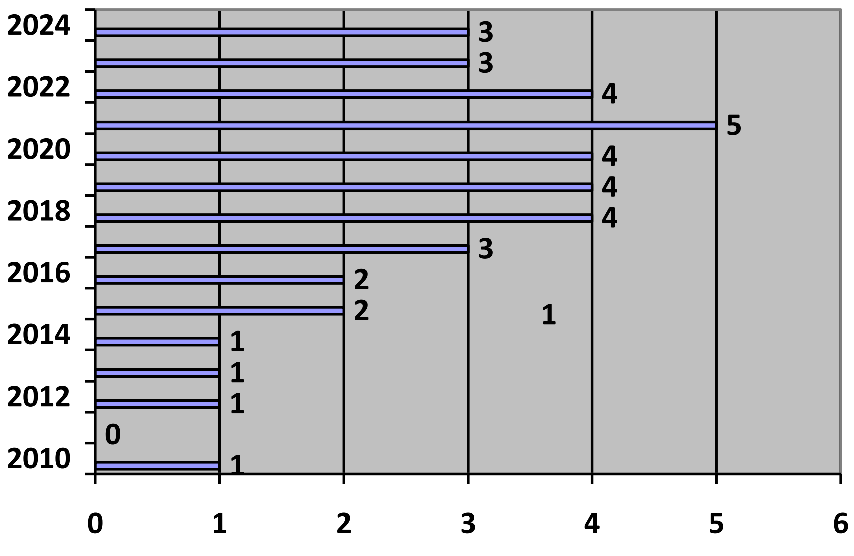

Figure 2. Publication trends (by year, n = 38)

The publication trend presented in Figure 1 shows a steady increase in research on earthquake-related technologies in physics education, particularly after 2015. Between 2010 and 2014, the number of studies was minimal, with only one or two publications per year, indicating that this field was still emerging. A significant increase occurred between 2016 and 2020, reaching a peak in 2020 with five publications. This surge reflects the rising global awareness of integrating STEM education, disaster preparedness, and Education for Sustainable Development (ESD) into science learning. In subsequent years, from 2022 to 2024, the trend remained stable with three to four studies annually, suggesting that this area has become a consistent focus of scholarly attention. Overall, the figure illustrates that research on earthquake technologies in physics education is relatively recent but continues to develop as a recognized field within sustainable science education.

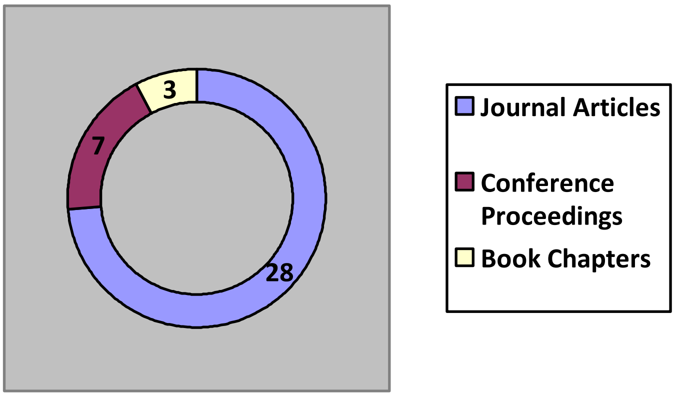

Figure 3. Types of publications (n = 38)

Figure 3 illustrates the distribution of publication types reviewed in this study. The majority of the studies were published as peer-reviewed journal articles, indicating that research on earthquake-related technologies in physics education has gained solid academic recognition. A smaller proportion appeared in conference proceedings, reflecting contributions from scholarly forums that often serve as platforms for preliminary findings. Meanwhile, only a limited number of studies were published as book chapters, suggesting that this research area is still predominantly disseminated through journals rather than edited volumes.

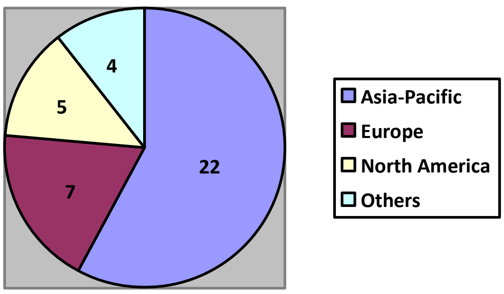

Figure 4. Geographic contexts (n = 38)

Figure 4 shows the geographical distribution of the reviewed studies. The Asia-Pacific region dominates with 22 publications, reflecting the strong emphasis on earthquake-related education in countries highly vulnerable to seismic hazards such as Indonesia, Japan, and the Philippines. Europe contributes seven studies, while North America accounts for five, indicating moderate engagement in this research field. The remaining four studies come from other regions, showing that global participation is present but less widespread. Overall, the concentration of research in the Asia-Pacific highlights the urgent need to integrate earthquake technologies into physics education in disaster-prone contexts. Meanwhile, contributions from Europe and North America demonstrate a growing international recognition of this issue within the broader Education for Sustainable Development (ESD) agenda.

Technological approaches in earthquake education

The use of technology in teaching about earthquakes in physics encompasses three main approaches: digital simulation and VR/AR, real-time sensors, and physical models. VR/AR-based digital simulations excel at providing an immersive experience that helps students understand seismic wave propagation, although they are constrained by cost and equipment requirements. Meanwhile, the use of sensors and real-time data enables students to access actual phenomena, thereby enhancing their data analysis skills. However, it is highly dependent on a robust technological infrastructure. On the other hand, physical models, such as shake tables, are relatively inexpensive and accessible, and are very effective for experiment-based learning; however, their limitations lie in scale and accuracy. Thus, the complementary integration of these three types of technology can produce a richer learning experience, combining abstract visualisation, real data, and hands-on practice.

Table 1. Technological approaches in earthquake education

Technology	Implementation Examples	Excess	Limitations
Digital Simulation & VR/AR	Earthquake VR Lab, a computer-based or mobile earthquake simulation application	Provides interactive and immersive visualization.- Facilitates the understanding of abstract concepts (seismic waves, energy propagation).- Safe, as it does not involve real risks.	Requires special devices (such as VR headsets/PCs with high specifications).- Implementation costs are relatively expensive.- Requires adequate digital literacy for teachers and students.
Sensor & Data Real-time	Smartphone accelerometer, IoT-based seismographs in schools, data from BMKG/USGS	Connecting theory to real-world phenomena through real-time data.- Improving students' data analysis skills.- Encouraging inquiry-based learning.	Depends on the network/internet infrastructure.- Sensor calibration needs attention.- Not all schools have access to seismograph devices.
Model Fisik (Shake Tables & Analog Devices)	Simple (manual/automatic) shake table, model of a miniature building	Provides a hands-on experience.- Easy to understand and inexpensive to create.-	Limited scale, does not fully represent real earthquake conditions.- Simulation accuracy is

Technology	Implementation Examples	Excess	Limitations
	structure for durability test	Encourages collaborative and creative experimentation.	lower than digital/VR.- Requires space and maintenance of physical devices.

Pedagogical integration into physics learning

The integration of earthquake technologies into physics learning is achieved by directly connecting them to core topics, such as mechanical waves, dynamics, energy, vibrations, and resonance. For example, seismograph data or digital simulations are used to strengthen students' understanding of longitudinal and transverse waves. At the same time, shake tables help them observe the relationship between natural frequency and resonance in building structures. In this way, abstract physics concepts can be contextualized through real-world phenomena relevant to disaster mitigation and management.

From the perspective of teaching strategies, various approaches are employed. Inquiry-based learning encourages students to independently explore earthquake data or physical models, thereby fostering critical thinking skills. Project-based learning emphasizes collaboration, for instance, through projects on designing earthquake-resistant building models or developing simple sensor-based applications. Gamification is widely applied, supported by VR/AR applications that simulate earthquake scenarios, thereby enhancing both emotional engagement and conceptual understanding. Meanwhile, problem-solving approaches engage students in analyzing case studies of building damage caused by earthquakes and seeking solutions based on physics principles.

Table 2. Pedagogical integration of earthquake technologies into physics learning

Core Physics Topics	Instructional Strategies	Pedagogical Impact
Mechanical Waves, Seismic Propagation	Inquiry-based learning (exploring seismic data, investigating longitudinal & transverse waves)	Enhances scientific reasoning- Connects abstract concepts with real phenomena- Reduces misconceptions about wave behavior
Resonance, Vibrations, Energy Transfer	Project-based learning (designing earthquake-resistant building models, shake table experiments)	Fosters collaboration and critical thinking- Bridges theory with engineering applications- Encourages creativity in problem-solving
Dynamics, Structural Response to Earthquakes	Problem-solving approaches (case analysis of building damage, disaster mitigation tasks)	Strengthens analytical skills by applying physics concepts to real-world contexts and building awareness of disaster risk reduction.
Cross-topic Integration (Waves, Energy, Resonance)	Gamification (interactive VR/AR simulations, game-based challenges)	Increases motivation and student engagement- Promotes curiosity and persistence- Improves long-term retention through immersive experiences

Research findings suggest that integrating earthquake technologies into physics learning has a positive impact on students' engagement and conceptual understanding. The use of interactive simulations and real-time data has been shown to enhance learning motivation, as students perceive the topics as highly relevant to real-life contexts. Moreover, active participation through experiments and collaborative projects deepens the understanding of fundamental physics concepts, particularly in relation to issues of Education for Sustainable Development (ESD), such as disaster risk reduction and sustainable development.

Contribution to Education for Sustainable Development (ESD)

The integration of earthquake-related technologies into physics learning significantly contributes to the development of sustainability competencies, particularly by fostering problem-solving, decision-making, and risk reduction awareness among students. By engaging with real-world disaster scenarios through simulations, sensors, and hands-on models, students not only strengthen their conceptual understanding of physics but also acquire essential skills for sustainable living.

Table 3. Contribution of earthquake technologies in physics learning to ESD competencies and SDGs

Earthquake Technology	Related Physics Concept	ESD Competency Developed	Linked SDGs
Digital Simulations (VR/AR)	Wave propagation, energy transfer	Problem-solving, critical thinking, and conceptual understanding	SDG 4 (Quality Education), SDG 11 (Sustainable Cities and Communities)
Seismograph Data & Real-time Sensors	Longitudinal & transverse waves, dynamics	Data analysis, decision-making, and scientific literacy	SDG 4, SDG 11
Shake Tables & Physical Models	Resonance, natural frequency, vibrations	Design skills, collaboration, and disaster risk reduction awareness	SDG 4, SDG 11
Gamified Earthquake Scenarios	Cross-topic integration (waves, energy, resonance)	Motivation, engagement, persistence, risk-awareness	SDG 4, SDG 11

This educational approach directly supports SDG 4 (Quality Education) by promoting relevant, inclusive, and applied science learning, while simultaneously aligning with SDG 11 (Sustainable Cities and Communities) through the cultivation of disaster preparedness and resilience. Moreover, physics education plays a pivotal role in nurturing disaster literacy, empowering learners to critically analyze risks, propose mitigation strategies, and apply scientific principles to enhance community safety. In this way, integrating earthquake technologies into the physics curriculum ensures that science education moves beyond theoretical knowledge, equipping students with the competencies necessary for sustainable development and resilient societies.

Learning outcomes reported

The reviewed studies consistently reported positive learning outcomes from integrating earthquake-related technologies into physics education. Among the most notable achievements are improvements in scientific literacy, as students were able to connect theoretical physics concepts with real-world disaster contexts, and the development of critical thinking skills, particularly through inquiry- and project-based activities. Furthermore, students demonstrated enhanced risk awareness and preparedness, showing greater understanding of seismic hazards and appropriate mitigation strategies.

Table 4. Reported learning outcomes from integrating earthquake technologies into physics education

Learning Outcome	Example Technology / Strategy	Evidence Reported
Scientific Literacy	Use of seismograph data, VR simulations of seismic waves	Students connected physics concepts (wave propagation, resonance) with real-world disaster phenomena
Critical Thinking	Inquiry-based investigations, project-based design of earthquake-resistant structures	Improved reasoning, problem-solving, and ability to apply physics in authentic contexts
Risk Awareness & Preparedness	Shake table experiments, gamified earthquake scenarios	Increased understanding of hazard impacts and appropriate mitigation strategies
Collaboration Skills	Group projects using sensor-based applications or building models	Strengthened teamwork, communication, and co-construction of knowledge
(Limited) Long-term Behavioral Change	Few longitudinal or community-based interventions	Short-term gains are documented, but sustained preparedness practices remain underexplored.

Collaborative projects involving shake tables, real-time data analysis, or sensor-based applications also fostered stronger teamwork and communication skills, aligning with the broader goals of 21st-century competencies. However, despite these encouraging findings, outcomes related to long-term behavioral change such as sustained preparedness practices or community-level resilience remain underexplored. This suggests the need for future research to extend beyond short-term cognitive gains and investigate how physics education can contribute to lasting changes in attitudes and behaviors toward disaster risk reduction.

Challenges and limitations identified

Despite the promising findings, several challenges and limitations were consistently identified across the reviewed studies. One significant barrier is the limited access to technology in developing countries, where the availability of VR/AR devices, seismic sensors, or even reliable internet infrastructure remains uneven. In addition, curriculum-related issues persist, as many physics curricula have yet to systematically incorporate disaster-related technologies or explicitly link them with learning outcomes in sustainability and disaster preparedness. Another challenge concerns teachers' competencies, since the effective use of earthquake technologies requires adequate digital literacy and pedagogical skills, highlighting the need for continuous professional development. Finally, the literature reveals a lack of longitudinal research that examines the long-term impacts of these innovations, such as sustained preparedness behaviors or community resilience. These limitations indicate that while current practices demonstrate significant potential, structural and systemic barriers must be addressed to ensure the sustainable integration of earthquake technologies into physics education.

Future research directions

Future research on integrating earthquake technologies into physics education offers several promising directions. First, there is considerable potential in developing AI-based earthquake simulations and IoT-enabled sensor networks that can be implemented in schools to provide real-time, adaptive, and interactive learning experiences. Second, advancing cross-disciplinary approaches that combine physics, geography, and environmental education could foster more holistic disaster literacy, enabling students to understand earthquakes not only as physical phenomena but also as socio-environmental challenges. Third, comparative international studies are necessary to assess the effectiveness of technology-enhanced earthquake education across diverse cultural and educational contexts, particularly between high-resource and resource-limited settings. Finally, the development of assessment tools specifically designed to measure ESD-related competencies such as resilience, preparedness, and sustainability awareness would provide valuable insights into the long-term educational impact of earthquake-focused physics learning. Together, these directions help bridge existing gaps and ensure that physics education makes a meaningful contribution to disaster risk reduction and sustainable development.

Discussion

The findings of this review confirm that integrating earthquake-related technologies into physics education substantially enhances students' engagement, scientific literacy, and disaster awareness. This aligns with previous studies highlighting the role of contextualized science learning in disaster-prone regions, where abstract physics concepts can be meaningfully connected to students' daily experiences with seismic risks (O'Reilly et al., 2020; Suwito et al., 2022). By embedding simulations, sensors, and physical models into lessons on waves, resonance, and energy transfer, physics classrooms can serve as transformative spaces that bridge theoretical knowledge with practical disaster preparedness. Such integration directly supports the ESD agenda, particularly SDG 4 and SDG 11, by equipping learners with competencies needed for resilience and sustainable living (Fekete, 2021; Hu et al., 2022).

The review also demonstrates that diverse pedagogical approaches—such as inquiry-based learning, project-based learning, and gamification—maximize the benefits of earthquake technologies in physics classrooms. Inquiry-based tasks, like analyzing seismic data, promote deeper conceptual understanding and critical reasoning (Shaw et al., 2021; Rachman et al., 2023). Meanwhile, project-based activities using shake tables or structural models enhance collaboration and creativity, allowing students to translate theory into engineering applications (Lestari et al., 2021; Bianchi-Berger, 2025). Gamified approaches supported by VR/AR applications significantly increase engagement, persistence, and emotional connection to the learning process (Vidak et al., 2023; Guo et al., 2023). These results reaffirm the argument that physics education, when technologically enriched, not only strengthens disciplinary knowledge but also nurtures higher-order thinking and problem-solving skills essential for sustainability.

However, the findings reveal persistent challenges that limit the widespread adoption of earthquake technologies in physics education. One major constraint is unequal access to high-tech resources such as AR/VR devices and real-time sensors, which remain costly and infrastructure-dependent, especially in developing contexts (Kapp et al., 2020; Yoon et al., 2021). In addition, many teachers lack adequate digital literacy and pedagogical training to effectively implement these tools (Özdemir & Yildiz, 2021; Suparno et al., 2022). These structural barriers contribute to inconsistencies in instructional quality and prevent the technologies from achieving their full educational potential. Without targeted support in teacher professional development and resource allocation, the transformative role of physics education in disaster literacy will remain underutilized.

Another important limitation identified is the lack of longitudinal research examining the sustained impact of technology-enhanced earthquake education. While short-term improvements in engagement, conceptual understanding, and risk awareness are consistently reported, few studies address whether these gains translate into long-term preparedness behaviors or community resilience (Takeda, 2018; Wang et al., 2023; Masroni & Elsafitra, 2024). This gap underscores the need for more robust methodologies and long-term interventions that assess how physics learning can influence students' disaster-related decision-making and actions beyond the classroom. Future research should also develop reliable assessment instruments tailored to measure ESD competencies such as resilience, sustainability awareness, and disaster preparedness (Tran et al., 2022; Ji et al., 2023).

Taken together, this discussion highlights that integrating earthquake technologies into physics learning is not merely an instructional innovation but a crucial pathway toward achieving sustainable education in disaster-prone societies. While positive impacts on engagement, scientific literacy, and risk awareness are well-documented, systemic challenges related to accessibility, teacher capacity, and long-term evaluation must be addressed. Future directions should prioritize AI-based simulations, IoT-enabled sensors, and cross-disciplinary approaches that connect physics with geography and environmental education (Zhou et al., 2019; Rajabi et al., 2022). By doing so, physics education can evolve into a platform that not only explains the mechanics of earthquakes but also empowers students to become agents of resilience and sustainability within their communities.

CONCLUSION

Fundamental Finding: This review shows that integrating earthquake technologies into physics education enhances students' engagement, conceptual understanding, and disaster literacy, bridging theory and real-world applications within the ESD framework. **Implication:** Such integration supports SDG 4 (Quality Education) and SDG 11 (Sustainable Cities and Communities) by fostering problem-solving, risk awareness, and preparedness, highlighting the need for stronger curricular and pedagogical adoption. **Limitation:** Access to technology, limited teacher competence, and the lack of longitudinal studies remain significant barriers to sustainable implementation. **Future Research:** Future studies should develop AI- and IoT-based tools, promote cross-disciplinary approaches, conduct comparative international research, and design assessment instruments to measure ESD competencies more effectively.

AUTHOR CONTRIBUTIONS

Hanan Zaki Alhusni contributed to the development of the methodology, data analysis, sourcing of references, and drafting of the manuscript. **Riski Ramadani** contributed to the data curation, literature screening, and preparation of visualization materials. **Binar Kurnia Prahani** contributed to the conceptual framework, research design, and validation of the study. **Titin Sunarti** contributed to the supervision, critical review, and refinement of the manuscript. **Madlazim** contributed to the resources, and data verification. **Muhammad Rey Dafa Ahmadi** contributed to final editing of the manuscript. All listed authors have read and approved the final version of this article.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest, either financial or personal, that may have influenced the content or outcome of this study.

ETHICAL COMPLIANCE STATEMENT

This manuscript adheres to the principles of research and publication ethics. The authors affirm that the work is original, conducted with academic integrity, and free from any unethical practices, including plagiarism.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors confirm that no AI-based technologies were used in the preparation, analysis, or writing of this manuscript. Only standard academic tools such as Mendeley (for reference management and citation formatting) and VOSviewer (for bibliometric mapping and visualization) were employed. All stages of the research and manuscript preparation were carried out directly by the authors. The final responsibility for the content of this manuscript rests entirely with the authors.

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