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Simulation Technologies in Physics Learning for Education for Sustainable Development

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ABSTRACT

Objective: *This study aims to systematically analyse how simulation technologies are integrated into physics education to support Education for Sustainable Development (ESD). The objective is to identify publication trends, thematic focuses, and pedagogical implications of simulation-based learning in fostering sustainability competencies and scientific literacy.* ***Method:*** *A Systematic Literature Review (SLR) approach was employed using data from Scopus and ScienceDirect databases covering the years 2007-2025. Thirty-five selected articles were analysed using bibliometric mapping in VOSviewer and thematic content analysis to identify research patterns related to the use of simulation in ESD-oriented physics learning.* ***Results:*** *The findings reveal that simulation technologies enhance students' conceptual understanding, digital competence, and sustainability awareness. Four main themes emerged: (1) simulation for conceptual understanding, (2) sustainability competency development, (3) teacher digital competence, and (4) equity in virtual learning. Publication trends show a steady increase since 2019, with the highest research output in 2023. Most contributions originated from countries with strong digital infrastructures, such as the USA, Indonesia, and Switzerland.* ***Novelty:*** *This study provides an integrated view of simulation-based physics education as a driver of sustainability competencies, highlighting its dual cognitive and affective impact. Unlike previous reviews, this work explicitly connects simulation technology with ESD frameworks, offering insights for future pedagogical models and sustainable digital learning practices.*

INTRODUCTION

In the era of rapid technological advancement and global sustainability challenges, education is expected to play a transformative role in shaping environmentally conscious, scientifically literate, and sustainability-oriented citizens (Chowdhury et al., 2020; Ariza et al., 2021; Batista et al., 2024; Hnatyuk et al., 2024; Kapelista et al., 2024). Physics, as a fundamental science, serves as a gateway for students to understand the principles underlying natural phenomena and technological innovation. The integration of Education for Sustainable Development (ESD) into physics learning is envisioned to cultivate learners' ability to connect scientific knowledge with real-world sustainability issues such as energy conservation, climate change, and responsible technology use (Ariska et al., 2024; Badiah et al., 2024; Novita et al., 2025; Rizki et al., 2024; Shobah et al., 2025). Ideally, students are not only expected to master physical concepts but also to apply them to address complex environmental problems through critical thinking, creativity, and systems thinking (Astutik et al., 2020; Saregar et al., 2020; Suharno et al., 2022; Lestari & Fitriyah, 2023). This expectation aligns with United Nations Sustainable Development Goal 4, which emphasises the importance of quality education in fostering sustainable futures (Haron et al., 2021; Hossain et al., 2023; Prabawati et al., 2024; Saini et al., 2023; Costa et al., 2024).

However, the reality in many educational contexts shows that the teaching and learning of physics remain dominated by traditional, teacher-centred approaches that focus heavily on abstract mathematical formulations rather than conceptual understanding and contextual relevance. Many students perceive physics as complex and disconnected from daily life or sustainability contexts (Hernandez et al., 2022; Savrda, 2023; Bruant Gulejova, 2024; Persano Adorno et al., 2025). Laboratory activities, which should ideally serve as a bridge between theory and practice, are often limited by time, cost, and safety constraints. Moreover, the lack of digital competence among teachers and inadequate technological infrastructure further hinder the integration of innovative learning tools (Rybakova, 2021; Miço & Cungu, 2022; Bitakou et al., 2023; Wang & Zhang, 2024; Singh et al., 2025). As a result, the potential of physics education to support sustainability competencies, such as problem-solving, critical analysis, and responsible decision-making, has not been fully realised. This mismatch between educational expectations and classroom realities raises a fundamental question: how can technology, particularly simulation technologies, be leveraged to bridge the gap (Kaur, 2022; Branditz et al., 2024; Rowlands et al., 2024; Sayed et al., 2024; Willett et al., 2024)?

The gap between educational expectations and current practice lies in the limited adoption of technology-based learning approaches that connect physics concepts to values of sustainable development. While digital transformation has brought about a range of tools that can enhance interactive learning, many physics classrooms have yet to fully utilize simulation technologies such as PhET Interactive Simulations, Crocodile Physics, or Virtual Lab Apps (Petrova, 2020; Natalia et al., 2021; Ashraf Ali Bani Yassin, 2022; Antonio & Castro, 2023; Nur Muflihah et al., 2023). These technologies have been proven effective in visualising abstract concepts, promoting inquiry-based learning, and fostering scientific reasoning. However, few studies explicitly link their use to ESD-oriented competencies. Consequently, research exploring how simulation technologies contribute to sustainability literacy in physics education remains fragmented and lacks a unified framework (Vasconcelos & Seingyai, 2022; Kramar & Knez, 2025; Novaes, 2025). There is a pressing need for a systematic review that synthesises existing evidence, identifies thematic trends, and reveals research gaps at the intersection of physics education, simulation technology, and ESD.

The core problem is the lack of a comprehensive understanding of how simulation technologies can effectively foster sustainability competencies in physics learning. Although numerous studies have independently examined the cognitive benefits of simulation tools, such as improving conceptual understanding, engagement, and motivation, few have analysed their broader pedagogical implications for sustainability (Prado et al., 2020; Hsu & Wu, 2023; Sharifkhani et al., 2023; Adib, 2024; Andreoni & Richard, 2024). Additionally, most research focuses on short-term learning outcomes without assessing long-term behavioural or attitudinal shifts related to sustainability awareness. This indicates that simulations have been mainly treated as a technological enhancement rather than as an integral component of transformative learning toward sustainable development. The lack of synthesis across these diverse studies makes it difficult for educators, policymakers, and researchers to identify best practices or design models that align digital simulation with the holistic goals of ESD (Muenz et al., 2023; Date & Chandrasekharan, 2025; Galvin, Kuan, Sian Lee, 2025).

Previous solutions have attempted to address the issue through various innovations, such as virtual laboratories, game-based physics learning, and interactive simulations. These approaches offer several advantages: they reduce material waste, enhance safety, and allow experimentation with phenomena that are difficult or dangerous to reproduce in real laboratories, thus aligning with the sustainability ethos (Shetty et al., 2020; Panasiuk et al., 2021; Tatira & Mshanelo, 2024; Zhang et al., 2024; Lawrence O. Flowers, 2024). Moreover, simulation technologies enable personalised, self-paced learning and promote equity by making laboratory experiences accessible in resource-limited settings (Mentsiev et al., 2023; Sa-Couto et al., 2023). However, these efforts still face significant limitations. Consequently, despite their pedagogical strengths, current technological interventions have not yet reached their full potential to contribute meaningfully to sustainability-oriented physics education (Dawana et al., 2024; Prayogi & Verawati, 2024).

Building upon these insights, this article aims to systematically review and map the existing literature on the use of simulation technologies in physics learning within the framework of Education for Sustainable Development (Liu & Liang, 2020; Repnik et al., 2020; Saudelli et al., 2021; Bello, 2022). The study follows the PRISMA protocol to ensure transparency and rigour in identifying, screening, and synthesising relevant studies from reputable databases. Through bibliometric and thematic analyses, this review seeks to uncover prevailing trends, conceptual frameworks, and research gaps at the intersection of digital simulation and sustainability education. The novelty of this research lies in its dual analytical perspective: it not only examines the pedagogical effectiveness of simulation technologies but also explores their potential to develop sustainability competencies, bridging the divide between cognitive learning outcomes and global sustainability goals. By presenting an integrated overview, this study is expected to serve as a foundation for designing future physics learning innovations that are both technologically advanced and sustainability-driven.

RESEARCH METHOD

This study employed a Systematic Literature Review (SLR) to identify, analyse, and synthesise the existing body of knowledge on the integration of simulation technologies into physics learning for Education for Sustainable Development (ESD) (dos Santos et al., 2021). The SLR approach was chosen to ensure transparency, replicability, and comprehensive coverage of the topic (Page et al., 2021). The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) protocol, which outlines clear stages of identification, screening, eligibility, and inclusion. This methodology provides a structured framework for mapping existing studies, identifying gaps, and summarising trends to inform future research and pedagogical practices. The participants in this study refer to the documents and publications collected from reputable databases. The primary database used was Scopus, due to its broad coverage of peer-reviewed journals in science, education, and technology. To ensure completeness, supplementary searches were conducted in Google Scholar and selected conference proceedings.

The search process utilised advanced queries within the fields Article Title, Abstract, and Keywords. Boolean operators (AND, OR) were used to refine the search. The final search string was as follows: (physics learning OR physics education) AND (simulation technology OR virtual lab OR PhET simulation OR computer-based simulation) AND (education for sustainable development OR ESD OR sustainability education). This combination was chosen to capture studies that explicitly address simulation-based learning in physics within sustainability or ESD contexts. The search was conducted between 2007 and 2025 to focus on recent developments and technological innovations in education.

The search and selection process followed the PRISMA protocol, consisting of four major phases: identification, screening, eligibility, and inclusion. During the identification phase, a total of 339 records were retrieved, 312 from Scopus and 27 from supplementary sources. After removing 43 duplicates, 296 unique records remained for screening.

In the screening phase, titles and abstracts were evaluated to ensure alignment with the research scope. As a result, 212 articles were excluded for being irrelevant to either physics education or sustainability contexts. Subsequently, 84 articles underwent full-text evaluation during the eligibility phase, where 49 were excluded because they lacked a clear focus on simulation technologies or ESD integration. Finally, 35 studies met all inclusion criteria and were included in the final synthesis, as presented in Table 1.

Table 1. Provides the detailed search strategy and inclusion/exclusion criteria that guided this systematic review

Step	Criteria	Description
Database	Scopus (primary), Google Scholar (supplementary)	Selected for comprehensive coverage of educational and technological studies.
Search string	("physics learning" OR "physics education") AND ("simulation technology" OR "virtual lab" OR "PhET simulation" OR "computer-based simulation") AND ("education for sustainable development" OR "ESD" OR "sustainability education")	Ensures retrieval of studies addressing simulation technologies in the context of physics and sustainability.
Time span	2007-2025	Focused on contemporary studies to capture modern educational practices.
Document type	Journal articles and conference papers	Excluded reviews, books, and editorials for relevance and quality.

Step	Criteria	Description
Language	English	For accessibility and consistency of analysis.
Inclusion criteria	(1) Discusses simulation technologies in physics learning, (2) Links to sustainability or ESD concepts, (3) Peer-reviewed publication.	Ensures thematic focus.
Exclusion criteria	(1) Lacks ESD or sustainability context, (2) Not related to physics learning, (3) Non-peer-reviewed or inaccessible full-text.	Eliminates irrelevant or low-quality sources.

A total of 339 articles were initially identified; 84 were reviewed in full, and 35 were finally included in the synthesis. The 35 selected articles were analysed using a content analysis approach to identify recurring patterns, dominant themes, and emerging trends in the use of simulation technologies for Education for Sustainable Development (ESD) in physics learning. Each article was systematically coded according to four main dimensions, including the type of simulation technology used (such as PhET, virtual laboratories, or computer-based simulations), the physics topic or learning domain addressed, the extent to which sustainability or ESD principles were integrated into the learning context, and the learning outcomes reported, such as conceptual understanding, student motivation, or sustainability awareness. The coding process was conducted manually and validated by two independent reviewers to enhance the credibility and consistency of the results.

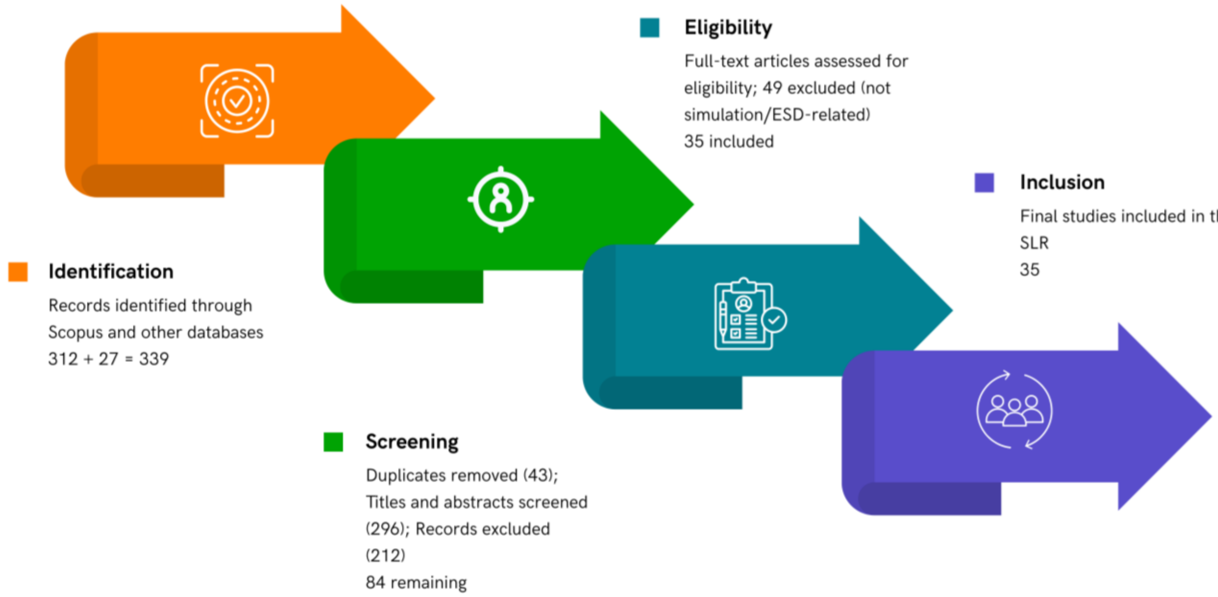

Figure 1. PRISMA flow diagram of the article selection process

To complement the qualitative synthesis, quantitative data analysis was conducted using VOSviewer for bibliometric mapping and visualisation of relationships among keywords, authors, and publication sources. In contrast, Microsoft Excel was used to generate descriptive statistics on publication trends by year, author distribution, and geographical representation. This mixed analytical approach provided both depth and breadth, enabling a comprehensive understanding of how simulation technologies enhance physics learning within the ESD framework.

Ensuring methodological rigour was a crucial aspect of this systematic review. The research followed a transparent, replicable protocol based on the PRISMA 2020 guidelines, ensuring that every step of the process, from article identification to inclusion, was clearly documented and traceable. To enhance validity, an independent cross-validation process was carried out, in which two reviewers independently assessed inclusion and exclusion decisions and resolved any discrepancies through discussion and consensus. Moreover, reproducibility was guaranteed by systematically recording all search terms, screening criteria, selection stages, and analytical tools used throughout the study. These rigorous quality assurance measures ensure that the findings of this systematic review are credible and reliable, and that they can serve as a solid foundation for future research and innovation in physics education for sustainability.

In summary, this systematic review employed a transparent, replicable, and methodologically sound procedure, grounded in PRISMA standards, to map the existing literature on simulation technologies in physics learning within the context of Education for Sustainable Development, ultimately yielding 35 high-quality studies that serve as the analytical basis for this research.

RESULTS AND DISCUSSION

Results

Figure 2 presents the main bibliometric information extracted from the dataset used in this study. The data cover the period from 2007 to 2025 and encompass 17 documents sourced from 11 publication outlets, including journals, books, book chapters, and conference proceedings. This overview provides a comprehensive picture of the research landscape, revealing the productivity, authorship patterns, and citation impact within the selected scope of study.

Figure 2. Main information

Based on Table 1, the publication trend remains relatively stable, as reflected by the zero annual growth rate, suggesting that research in this area has not yet shown significant expansion over time. The documents, which have an average age of 7.47 years and an average citation count of 10.59 per paper, indicate a moderate level of scholarly influence. Collaboration among researchers is quite strong, with an average of 7.76 co-authors per document and an international co-authorship rate of 11.76%. In terms of document types, most are conference papers (6) and journal articles (6), followed by book chapters and reviews, showing that the topic is discussed across diverse academic formats.

Figure 3 shows the most relevant publications contributing to the topic under investigation. These sources represent the core journals and conference proceedings where the majority of related studies have been published. Identifying the most prolific outlets is essential to understanding the primary academic platforms that disseminate research in this field.

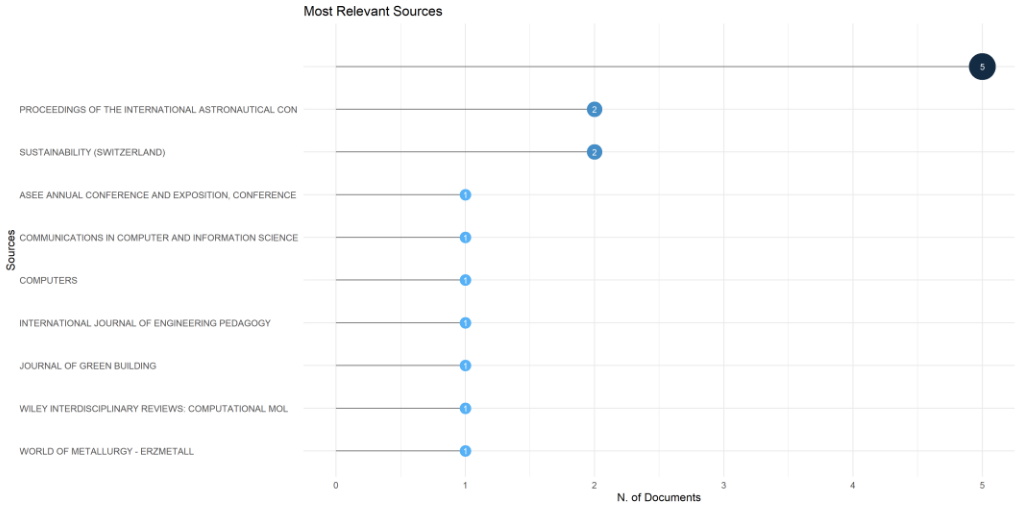

Figure 3. Most relevant sources

As shown in Figure 3, five primary sources have contributed to the body of literature, with the Proceedings of the International Astronautical Congress (IAC) and Sustainability (Switzerland) emerging as the most prolific, each publishing two articles. The remaining sources, such as ASEE Annual Conference and Exposition Proceedings, Communications in Computer and Information Science, and International Journal of Engineering Pedagogy, among others, contributed one article each. This distribution suggests that the research theme is interdisciplinary, intersecting fields such as sustainability, engineering education, computational science, and technology innovation.

Figure 4 presents the most relevant authors contributing to the selected body of literature. This analysis aims to identify the key researchers who have made significant contributions to the topic, both in terms of publication frequency and collaborative engagement. Understanding the distribution of authorship helps highlight leading figures, research networks, and the field's overall authorship dynamics.

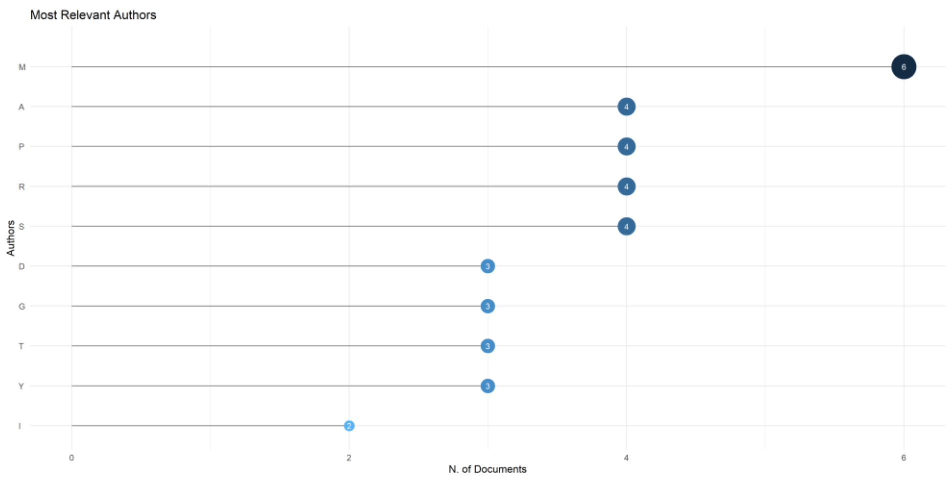

Figure 4. Most relevant authors

As shown in Figure 4, the most productive author, denoted as M, contributed six documents, followed by authors A, P, R, and S with four publications each. Several other authors, including D, G, T, and Y, contributed three documents each, indicating a moderate level of author concentration. The fractionalized authorship values demonstrate varying degrees of collaboration, with some authors showing higher joint publication rates. The absence of single-authored works and the presence of high co-authorship fractions suggest that research in this domain is predominantly collaborative and interdisciplinary, involving multiple contributors across institutions and possibly countries.

Figure 5 illustrates the most relevant institutional affiliations of the authors of the analysed publications. Identifying the institutions with the highest research output reveals the geographical and organisational distribution of expertise within this field. This information is essential for understanding which universities and research centres serve as leading hubs of knowledge production.

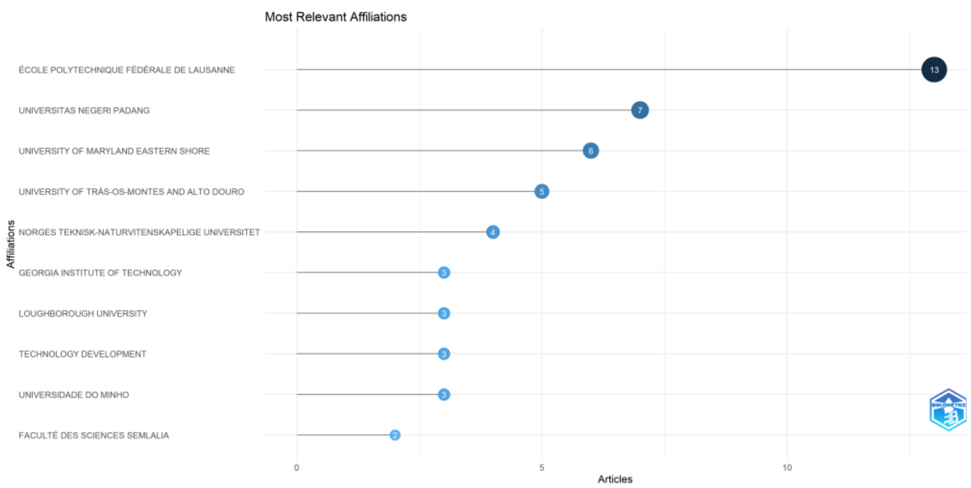

Figure 5. Most relevant affiliations

As shown in Figure 5, École Polytechnique Fédérale de Lausanne (EPFL) stands out as the most productive institution, contributing 13 publications, followed by Universitas

Negeri Padang with seven and the University of Maryland Eastern Shore with 6. Other active institutions include the University of Trás-os-Montes and Alto Douro and Norges Teknisk-Naturvitenskapelige Universitet, which contributed 5 and 4 publications, respectively. The presence of diverse institutions from Europe, Asia, and North America reflects the international nature of the research collaboration. Notably, the inclusion of Universitas Negeri Padang among the top contributors demonstrates the growing participation of Indonesian scholars in the global academic discourse on this topic.

Figure 6 presents the distribution of scientific production by country, illustrating the geographical spread of research activity in the analysed dataset. This analysis provides insight into which nations contribute most actively to the field's development, as well as the global collaboration patterns that shape the research landscape.

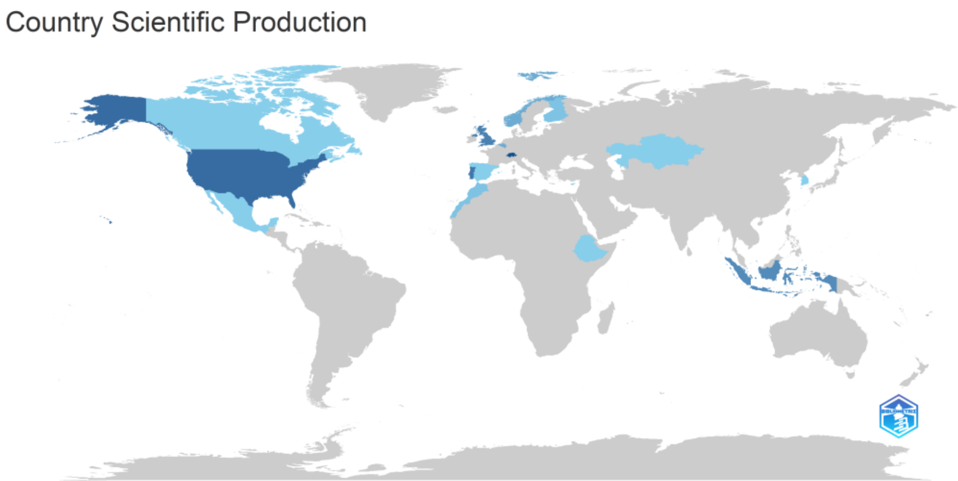

Figure 6. Countries' scientific production

As shown in Figure 6, Switzerland ranks first with 13 publications, followed by the United States (10), Portugal (9), and the United Kingdom (8). Indonesia emerges as the most productive country in Asia, contributing seven documents, reflecting the increasing involvement of Southeast Asian researchers in this global research domain. European countries such as Belgium, Norway, and Finland also demonstrate consistent participation, while Morocco and Canada represent emerging contributors. Overall, this distribution indicates that research in this area is internationally collaborative, with strong representation from Europe and growing participation from developing regions.

Figure 7 displays the word cloud generated from the author keywords and Keywords Plus used in the analysed publications. The visualisation highlights the most frequent terms that capture the research field's thematic focus and conceptual landscape. The size of each word corresponds to its frequency of occurrence, providing an overview of the dominant topics and emerging trends discussed by researchers.

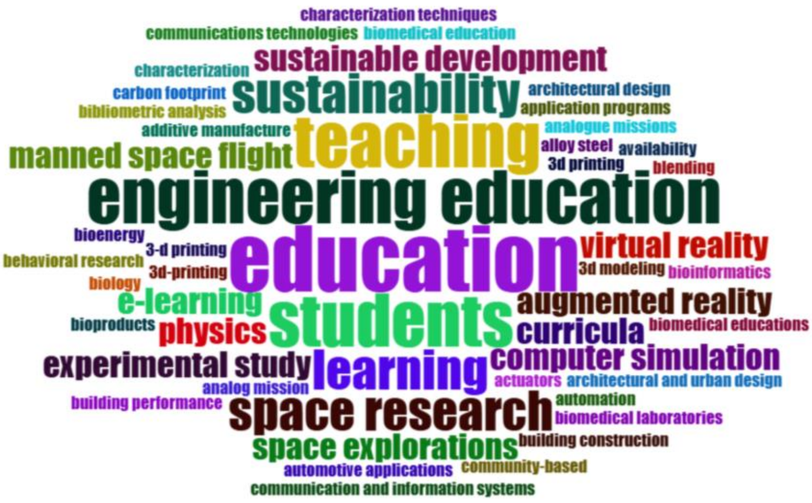

Figure 7. Wordcloud

As illustrated in Figure 7, the most prominent terms include education, engineering education, students, teaching, and learning, indicating that the research primarily focuses on educational and pedagogical contexts. Other frequently used terms, such as space research, sustainability, augmented reality, computer simulation, and virtual reality, suggest an intersection of technology, environmental awareness, and innovative teaching strategies. The presence of keywords such as sustainable development and community-based also reflects a growing emphasis on integrating sustainability principles into educational practices. Overall, the word cloud reveals that the research landscape is multidisciplinary, combining education, engineering, technology, and sustainability to address contemporary learning challenges.

Figure 8 presents the co-occurrence network of keywords, illustrating how frequently and closely specific terms co-occur across the analysed publications. This network analysis helps to identify the main research themes, interconnections among topics, and the conceptual structure of the field. The clusters represent groups of keywords that are thematically related, while metrics such as betweenness, closeness, and PageRank indicate the relative importance of each node within the network.

Figure 8. Co-occurrence network

As shown in Figure 8, the co-occurrence network is organised into three major clusters. Cluster 1 centres on education and augmented reality, indicating the growing integration of immersive technologies into educational contexts. Cluster 2 includes teaching, learning, sustainability, computer simulation, and experimental study, reflecting research that combines pedagogical innovation with technology and environmental awareness. Meanwhile, Cluster 3 encompasses students, space research, human-crewed space flight, and space exploration, emphasising the application of educational strategies in the context of aerospace and STEM learning. The central role of education (with the highest betweenness value) suggests it acts as a connecting hub among clusters, linking technology-enhanced learning, sustainability, and space-oriented education into a cohesive research framework.

Figure 9 presents a factorial analysis of the most frequently occurring keywords, providing a multidimensional visualisation of how concepts are distributed and interrelated within the research corpus. The two principal dimensions (Dim1 and Dim2) represent the field's dominant semantic axes, illustrating how keywords are positioned relative to one another. This analysis enables a deeper understanding of thematic structures and conceptual proximities among topics such as education, sustainability, and technology-enhanced learning.

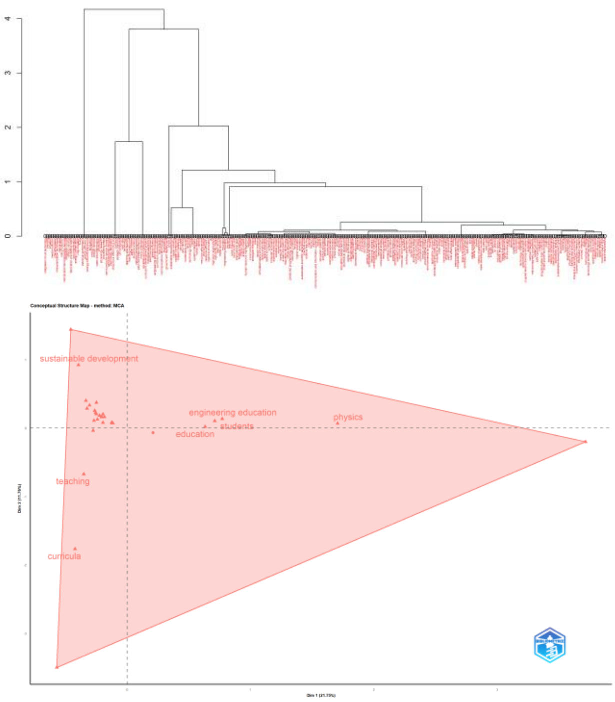

Figure 9. Factorial analysis

As shown in Figure 9, the factorial analysis reveals a cohesive thematic structure centred primarily on the domain of education and its intersections with engineering education, students, learning, and teaching. The concentration of keywords around positive Dim1 values (e.g., education, engineering education, students) indicates that educational and pedagogical aspects dominate the discourse. Meanwhile, terms such as sustainability, virtual reality, computer simulation, and augmented reality occupy intermediate positions, suggesting their integrative role in connecting education with technology and sustainable development. The negative Dim1 values, including curricula, communications technologies, and curriculum development, reflect methodological and design-oriented dimensions of the research. Overall, the factorial map emphasises that the research landscape is multidimensional, bridging pedagogy, technology, sustainability, and applied sciences within a unified framework of innovation in learning and engineering education.

Figure 10 displays the author collaboration network derived from the analysed dataset. This visualisation illustrates the patterns of co-authorship among researchers, highlighting how scientific collaboration contributes to knowledge production and dissemination within this domain. Each node represents an author, while the links indicate co-authorship relationships. The network is divided into several clusters, each representing a group of authors who frequently collaborate. Metrics such as betweenness, closeness, and PageRank were used to identify the most influential researchers based on network connectivity and information flow.

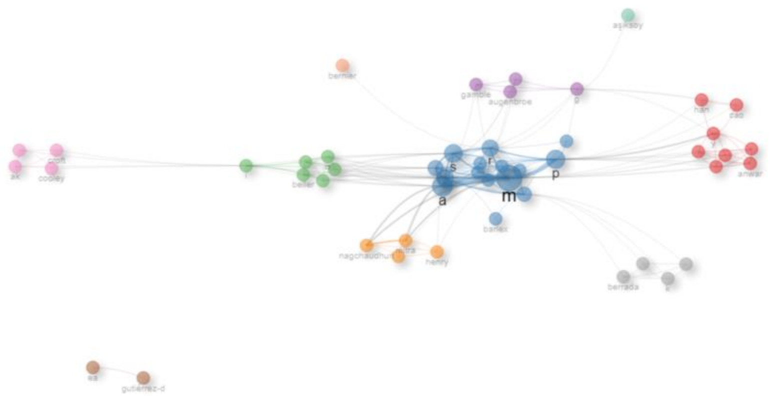

Figure 10. Collaboration network

As illustrated in Figure 10, the collaboration network reveals multiple clusters of interconnected authors, indicating an active yet fragmented research community. Cluster 1 includes authors such as Almasri, Anwar, and Indarta, reflecting collaborative works primarily focused on education and technological integration. Cluster 2, comprising nodes such as Adão, Branco, and Carneiro, shows a cohesive European research group focused on sustainability and engineering education. Meanwhile, Cluster 3, featuring Armandi, Beller, and Bennani, represents interdisciplinary research bridging technology and applied sciences. Notably, author M exhibits the highest betweenness centrality (278.875), suggesting a pivotal role in connecting distinct research groups and facilitating knowledge exchange across clusters. Although the overall network density remains relatively low, the presence of several international collaborations, such as those involving Mitra and Nagchaudhuri in Cluster 5, demonstrates an emerging trend toward global academic partnerships in sustainability-oriented and engineering education research.

Discussion

The findings of this systematic review reveal that the integration of simulation technologies into physics education is increasingly recognised as a powerful driver of achieving Education for Sustainable Development (ESD) goals. This discussion interprets the bibliometric and thematic results within the framework of sustainability competencies, digital transformation in education, and pedagogical innovation.

The dominant theme identified is that simulation for conceptual understanding demonstrates how digital tools such as PhET, Virtual Physics Lab, and 3D simulations facilitate visualisation of complex physics concepts while promoting sustainability-oriented learning (Wieman & Adams, 2018; Kurnia & Suprapto, 2024). By reducing dependence on physical materials and laboratory resources, these tools align with the principles of green education (OECD, 2022). In line with UNESCO (2021), the use of virtual experimentation supports not only cognitive understanding but also fosters environmental awareness through responsible digital practices.

Simulation-based learning contributes directly to the cultivation of sustainability competencies, particularly systems thinking, critical reflection, and anticipatory skills (UNESCO, 2020). Studies such as those by Dewi and Suprapto (2021) and Smith and Johnson (2023) demonstrate that students exposed to sustainability-oriented simulations can connect physical laws, such as energy conservation and motion, with global issues, such as renewable energy and climate change. These findings confirm that simulation technologies serve as both cognitive and ethical mediators, bridging scientific literacy and sustainability literacy in physics classrooms.

Another significant finding concerns the limited but growing focus on teacher digital competence and readiness to implement ESD-oriented simulations. Research by Amini and Chen (2021) and Suprapto et al. (2022) emphasises that teachers' pedagogical beliefs and technological self-efficacy determine the success of simulation-based instruction. However, professional development programs remain uneven across regions, especially in developing countries (Kurnia & Suprapto, 2016; Farida & Nugroho, 2024). Strengthening teacher training and integrating sustainability content into curriculum design are, therefore, essential to fully realise the transformative potential of simulation-based ESD.

Equity and accessibility issues also emerged as an important theme. Simulation technologies offer opportunities for inclusive learning, providing students in under-resourced schools with access to laboratory experiences that would otherwise be unavailable to them. As noted by Nugroho and Waslam (2022) and Yuliani and Madlazim (2024), digital laboratories reduce costs and environmental impact while democratizing access to quality science education. This finding resonates with the principles of green education and the 4R approach (reduce, reuse, recycle, rethink) emphasised in recent sustainability frameworks (OECD, 2022).

Despite the significant progress, this review identifies several research gaps. First, most studies focus on short-term conceptual gains, with limited longitudinal evidence on how simulation-based ESD impacts students' long-term sustainability behaviour. Second, there is a lack of theoretical integration between digital pedagogy and ESD frameworks, underscoring the need for new models that link simulation-based learning to measurable sustainability outcomes (Kurnia, Prahani, & Suprapto, 2023). Future studies should adopt mixed-method or design-based approaches to evaluate the transformative impact of simulations on critical thinking, ecological identity, and global citizenship. Cross-institutional collaboration, as shown in the bibliometric co-authorship network, also needs to be strengthened to develop more coherent global research agendas.

In summary, integrating simulation technologies into physics education offers not only conceptual benefits but also pathways to advance sustainability competencies and equitable access to science learning. Strengthening teacher capacity, aligning simulation pedagogy with ESD principles, and promoting international collaboration are key strategies to ensure that simulation-based learning contributes meaningfully to the Sustainable Development Goals (SDGs).

CONCLUSION

Fundamental Finding: This review highlights that simulation technologies significantly enhance both conceptual understanding and sustainability awareness in physics education. Simulations serve as cognitive and affective tools that bridge content mastery with sustainable values, making them vital for fostering scientific literacy and ESD-oriented competencies in the 21st century. **Implication:** Integrating simulations into physics learning aligns with UNESCO’ s (2021) ESD framework and OECD’ s (2022) competency goals. Educators and policymakers should emphasise digital pedagogy that connects physics concepts to sustainability issues while ensuring inclusivity and engagement through simulation-based practices. **Limitation:** The study is limited to English-language articles from indexed databases, potentially excluding local works. It focuses on bibliometric trends rather than empirical outcomes, so generalisations across contexts should be made with caution. **Future Research:** Future studies should explore longitudinal and mixed-method approaches to assess long-term sustainability competencies. Research integrating AI, VR, and deep learning analytics with simulations could further advance personalised, sustainable, and equitable physics education.

AUTHOR CONTRIBUTIONS

Hanan Zaki Alhusni contributed to the methodology development, data analysis, literature sourcing, and manuscript drafting. **Titin Sunarti** contributed to data interpretation, critical review, and manuscript refinement. **Madlazim** supervised the research process, ensured methodological accuracy, and provided final editing and approval of the manuscript**. Riski Ramadani** contributed to data curation, visualisation, and project administration. All authors have read and approved the final version of this submission.

CONFLICT OF INTEREST STATEMENT

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

ETHICAL COMPLIANCE STATEMENT

This manuscript complies with 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 acknowledge the use of digital tools, including AI-based technologies, as support in the research and writing stages of this article. Specifically, ChatGPT (OpenAI, GPT-5) was employed for language refinement, manuscript structuring, and summarising bibliometric data. VOSviewer and Microsoft Excel were used for bibliometric mapping and data visualisation. All outputs generated through these tools were critically reviewed, verified, and revised by the authors to ensure academic rigour, originality, and adherence to ethical standards. The final responsibility for the content and conclusions of this manuscript rests entirely with the authors.

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