

Global Trends and Research Directions in Technology Integration in Physics Education for SDG 4: A Bibliometric Analysis (2016–2025)

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ABSTRACT

Objective: This study examines the development and research potential of technology integration in physics education related to Sustainable Development Goal 4 (SDG 4) from 2016 to 2025. By mapping global scientific publications, this study identifies research trends, collaboration patterns, and emerging technological innovations that support inclusive and high-quality physics education. **Method:** A bibliometric analysis, combined with a systematic literature review following the PRISMA protocol, was employed. Data were retrieved from the Scopus database, resulting in 27,322 documents published between 2016 and 2025. After applying PRISMA screening stages – identification, screening, eligibility, and inclusion – 5 articles were selected for detailed analysis. Bibliometric mapping was conducted using VOSviewer and Bibliometrix (R-package) to visualize publication growth, author productivity, collaboration networks, and keyword co-occurrence. **Results:** The results indicate a significant increase in publications on technology-based physics learning, particularly after 2021, reflecting accelerated digital transformation in science education. The United States, India, China, and Indonesia are the most productive countries, demonstrating global participation in this research area. Keyword analysis highlights “education,” “sustainable development,” “engineering education,” and “technology” as dominant themes. At the same time, emerging topics such as “machine learning” and “augmented reality” indicate growing interest in advanced digital tools for physics learning. **Novelty:** This study provides a comprehensive bibliometric mapping of technology integration in physics education within the SDG 4 framework. It identifies future research directions involving artificial intelligence, immersive learning technologies, and innovative digital pedagogies.

INTRODUCTION

Education is a fundamental pillar of sustainable development because it directly improves human quality of life and strengthens national competitiveness. Within the global development agenda, the Sustainable Development Goals (SDGs) highlight SDG 4 as a critical objective to ensure inclusive, equitable, and high-quality education for all (Ferrer-Estévez & Chalmeta, 2021; Masuda et al., 2022; Saini et al., 2023). Achieving this goal requires continuous innovation in teaching and learning processes so that education systems can respond effectively to the demands of the 21st century, including the development of critical thinking, creativity, and problem-solving skills.

Physics education plays a particularly important role in this context because it fosters analytical reasoning and scientific literacy, which are essential for addressing global challenges in science, technology, and sustainability (Awwalina et al., 2025; Wahab et al., 2025). Unlike many other disciplines, physics often involves abstract concepts that require visualization, experimentation, and conceptual modeling. As a result, the integration of digital technologies such as simulations, virtual laboratories, artificial

intelligence, integrated learning environments, and interactive multimedia has become increasingly important to facilitate deeper conceptual understanding and improve student engagement.

Alongside rapid developments in digital innovation, educational practices have experienced significant transformation through the adoption of technology-enhanced learning environments. Recent advances in digital tools including online simulations, augmented and virtual reality, adaptive learning platforms, and data-driven instructional systems have expanded opportunities to make physics learning more interactive and accessible. These innovations allow educators to address conceptual difficulties, provide flexible learning experiences, and create student-centered instructional environments (Apata et al., 2025; Rad et al., 2022; Wilczyński, 2021). Consequently, integrating digital innovation into physics education has become a strategic pathway to support the achievement of SDG 4 by improving the quality and accessibility of science education.

Despite the growing number of studies investigating technology integration in education, existing research remains diverse and fragmented. Many studies focus on specific digital tools, limited classroom implementations, or particular educational contexts without providing a comprehensive understanding of broader research developments. Several bibliometric studies have examined digital education, STEM education, or sustainability-related learning; however, most address these themes at a general level rather than specifically analyzing the development of technology-enhanced physics education in the context of SDG-oriented educational goals (Prieto-Jiménez et al., 2021). As a result, there is still limited knowledge about how global research trends, collaboration patterns, and emerging thematic areas in physics education contribute to the broader agenda of quality education.

Over the past decade, publications on technology integration in physics education have grown substantially (Bitzenbauer, 2021). Nevertheless, the relationships among research themes, the evolution of collaborative networks, and the alignment of these studies with global educational priorities such as SDG 4 have not been systematically explored (Wang et al., 2023). This lack of comprehensive mapping creates challenges for educators, researchers, and policymakers in identifying dominant research directions, recognizing emerging topics, and determining whether existing research effectively supports sustainable educational development (Hölscher et al., 2021; Payne-Gifford et al., 2022). Without a clear understanding of these trends, efforts to integrate technological innovation into physics education may remain fragmented and less effective in supporting global educational goals (Jugembayeva & Murzagaliyeva, 2022).

Bibliometric analysis offers a systematic and transparent approach to examining scientific developments by mapping publication trends, collaboration networks, and thematic structures within a research field (Zhang et al., 2023). This approach allows researchers to identify influential publications, emerging research topics, and knowledge gaps that require further investigation (Almeida & Nascimento, 2022; Prahani et al., 2023). When combined with systematic review procedures such as PRISMA, bibliometric

analysis provides stronger methodological rigor and enhances the reliability of research findings (Xu et al., 2021). Furthermore, bibliometric studies oriented toward SDG-related research provide valuable insights into how educational innovations contribute to equity, quality, and sustainability in learning systems (Pham et al., 2023; Zhang et al., 2022), while also supporting evidence-based policy development (Bircan & Salah, 2021).

However, a comprehensive bibliometric mapping that specifically examines the intersection of digital innovation, physics education, and the global agenda of SDG 4 remains limited. Understanding how research in this area has evolved is essential for identifying emerging themes, guiding future research directions, and strengthening the role of physics education in achieving sustainable development goals. Therefore, this study aims to map global publication trends, thematic developments, and research directions related to technology integration in physics education from 2016 to 2025 using bibliometric analysis. In addition, this study seeks to examine how these research developments contribute to the broader objective of achieving SDG 4 (Quality Education).

RESEARCH METHOD

The present study employs a quantitative bibliometric design to analyze global publication trends in the integration of technology into physics education and their alignment with SDG 4 (Quality Education) during the 2016–2025 period. Bibliometric analysis examines the development of scientific literature through statistical evaluation of publication metadata such as authorship, citations, institutional affiliations, and keywords, allowing researchers to identify research productivity, collaboration networks, and thematic evolution within a field (Lintangesukmanjaya et al., 2025).

This study combines descriptive performance analysis and science mapping techniques. Performance analysis evaluates publication productivity and research impact, including annual publication trends, leading countries, institutions, and influential sources. Science mapping is used to visualize relationships among research components and to reveal the field's intellectual structure. This approach provides an objective and systematic understanding of research dynamics related to technology integration in physics education (Singh et al., 2021; Lyu et al., 2024).

The bibliographic data used in this study were retrieved from the Scopus database, which is widely recognized as one of the most comprehensive international scientific databases. Scopus was selected as the primary data source due to its broad coverage of peer-reviewed journals, rigorous indexing standards, and compatibility with bibliometric analysis tools. The dataset was retrieved using the search query: TITLE-ABS-KEY (“technology” AND “physics” AND (“sdgs” OR “sdg” OR (“sustainable” AND “development” AND “goal”))). This search generated an initial set of publications relevant to the research focus. All retrieved records were exported in CSV format for further analysis. To ensure transparency and methodological rigor in the article selection process, this study followed the PRISMA 2020 guidelines. The PRISMA framework was used because it provides a structured, systematic procedure for identifying, screening,

and selecting relevant studies while minimizing bias in the literature selection process. The selection procedure consisted of four stages:

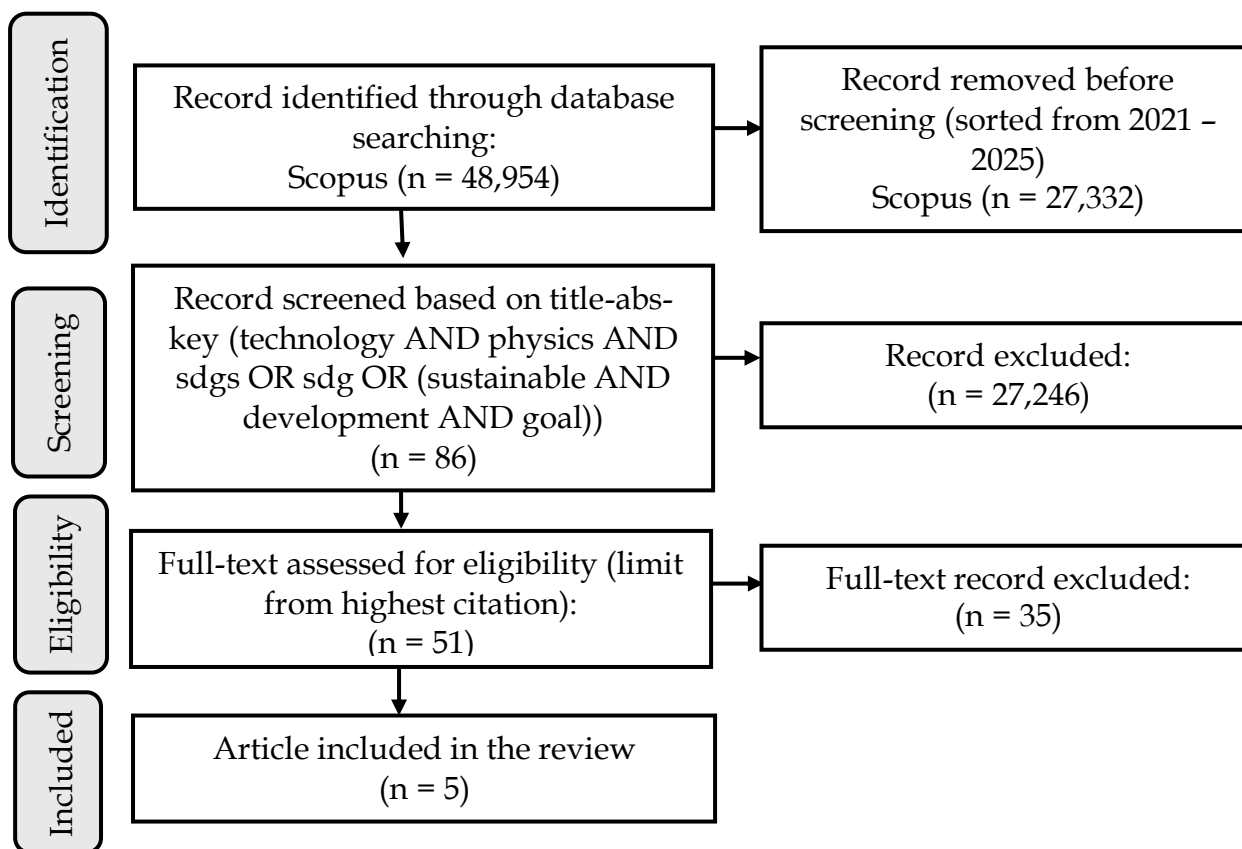


Figure 1. Systematic literature review information flow using PRISMA

The inclusion criteria applied in this study were publications indexed in Scopus, peer-reviewed journal articles written in English, highly cited publications, and studies published between 2016 and 2025. Meanwhile, documents such as conference papers, book chapters, editorials, and studies unrelated to physics education or educational technology were excluded from the dataset. The final dataset obtained through the PRISMA refinement served as the analytical sample, where each publication functioned as a unit of analysis to map publication patterns, collaboration structures, and thematic developments related to technology-based physics learning and its relevance to SDG 4.

Bibliometric instruments formed the core analytical tools in this study. The analysis was conducted using VOSviewer to visualize co-authorship networks, institutional linkages, international collaboration patterns, citation structures, and keyword co-occurrence clusters (Dewi & Rahayu, 2023; Lyu et al., 2025). In addition, the Bibliometric package in the R environment was used to perform descriptive bibliometric analyses, including annual publication trends, source impact evaluation, author productivity, and thematic evolution mapping (Khanra et al., 2022). These tools enabled both macro-level and micro-level analysis of the research landscape.

The data analysis was conducted through several stages. First, descriptive bibliometric indicators were generated to identify patterns of publication growth and research

productivity. Second, network analysis was used to map collaboration patterns among authors, institutions, and countries. Third, keyword co-occurrence analysis was performed to identify dominant research themes and emerging conceptual trends, as keyword relationships reflect the conceptual structure of a research domain and reveal major thematic clusters. Finally, the bibliometric findings were interpreted in relation to SDG 4 to evaluate how technological innovations in physics education contribute to advancing inclusive, equitable, and quality education (Karuppiah et al., 2023).

RESULTS AND DISCUSSION

Results

The Scopus-based publication analysis shows the growth of research on technology in physics education and its connection to SDG 4 during 2016–2025. The yearly distribution of articles, presented in Table 1, shows the distribution of articles published during 2016–2025. Instead of presenting the data solely in tabular form, the yearly distribution of publications is visualized graphically to highlight research trends and patterns better.

Table 1. Distribution of articles published during 2016–2025

Year	Number of Articles in Scopus
2016	1
2017	1
2018	1
2019	6
2020	2
2021	6
2022	16
2023	13
2024	24
2025	14

The analysis shows that the number of publications was relatively low during the early years of the observation period. Between 2016 and 2018, only one article was published each year, indicating that research on the intersection of technology integration in physics education and the SDG framework was still in its early stages. A noticeable increase occurred in 2019 with six publications, followed by a temporary decline in 2020 to two publications, which may reflect disruptions in academic productivity during the global pandemic.

Since 2021, the number of publications has increased significantly, from six in 2021 to sixteen in 2022 and thirteen in 2023. The highest number was recorded in 2024 with twenty-four publications, highlighting growing academic attention to the role of technology in supporting physics education aligned with SDG 4. Although the number decreased slightly to 14 publications in 2025, the overall trend still indicates substantial growth compared to the early years. Citation analysis also reveals that although early publications (2016–2018) were limited in number, several received considerable citations,

demonstrating their foundational role in shaping subsequent research, while later years show a gradual increase in citation activity reflecting the expanding influence of this research field.

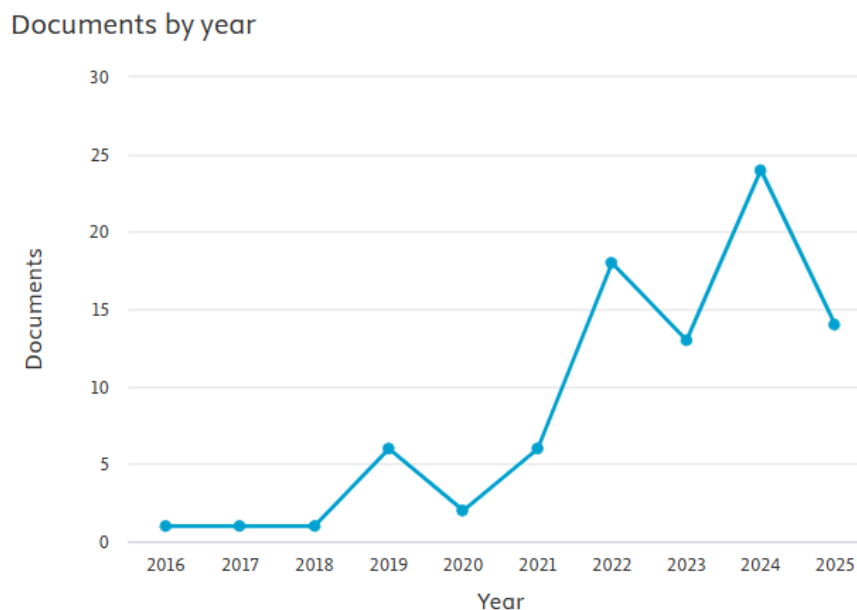


Figure 2. Annual publication and citation trends (2016–2025)

The distribution of document types shows how research on technology integration in physics education has been disseminated in the academic community. Conference papers dominate the publications with 31 documents (36%), followed by journal articles with 20 documents (23.3%), review papers with 15 (17.4%), and book chapters with 10 (11.6%), while other types, such as books, conference reviews, and notes, each contribute less than 10%. The dominance of conference papers indicates that this research field is still developing, with conferences serving as key platforms for presenting early-stage findings, emerging technological innovations, and exploratory studies that are often later expanded into journal articles and review papers with more comprehensive theoretical discussions and empirical validation. This pattern suggests that conferences serve as an initial stage of dissemination. At the same time, journal articles and reviews consolidate knowledge, reflecting the dynamic growth of research on technology integration in physics education and its increasing contribution to achieving SDG 4 through improved educational practices.

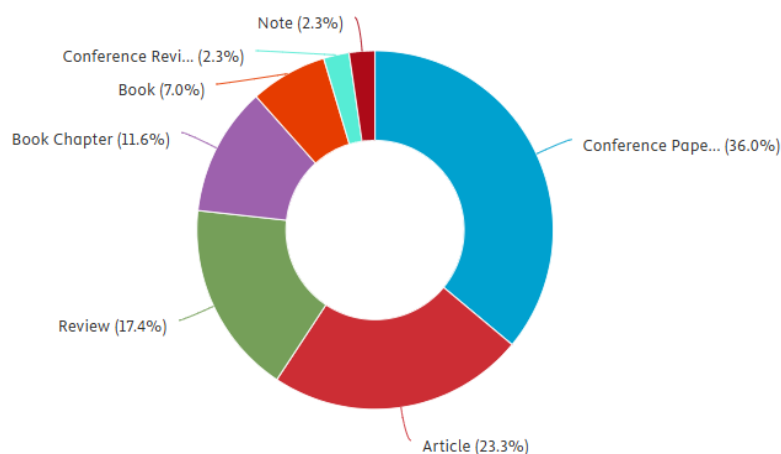
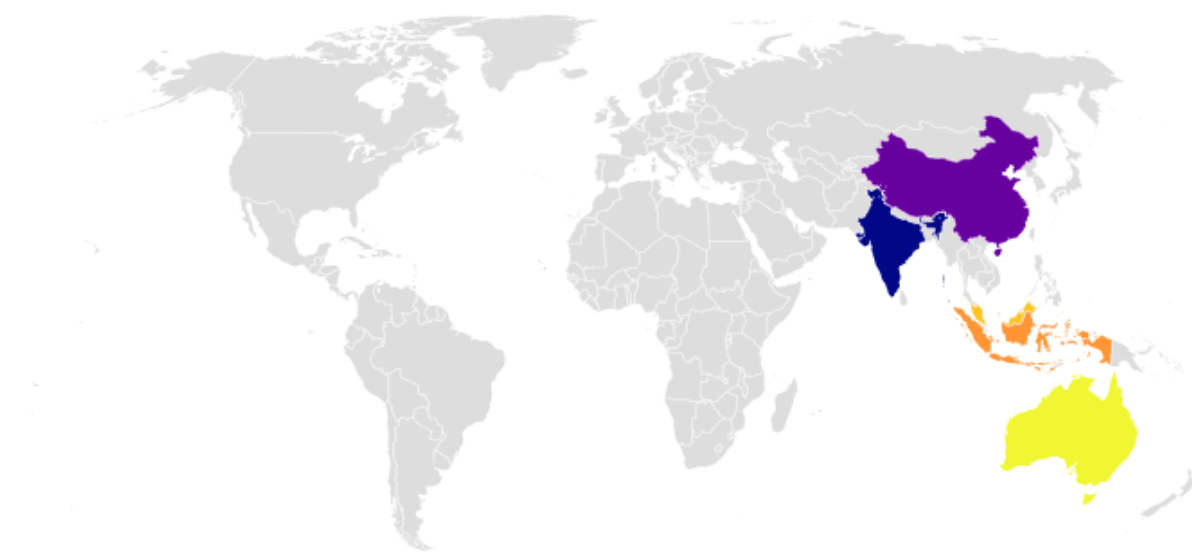


Figure 3. Distribution of Document Types

The analysis of country contributions shows that research on technology integration in physics education related to SDG 4 has gained global attention. Over the past decade, the United States has been the most productive country with 18 publications, followed by India (11) and China (10). Other major contributors include France and the United Kingdom, with 7 publications each; Germany, Indonesia, and Spain, with 6 each; and Malaysia and Australia, with 5 and 4, respectively. These results indicate that research activity is not limited to highly developed countries, as emerging and developing nations such as India, Indonesia, Malaysia, and Spain also make significant contributions, reflecting the growing global interest in technology-enhanced physics education to improve the quality of science education and support the achievement of sustainable development goals.

TOP Country Publishing Technology in Physics Learning for SDGs 4 (Quality Education)



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Figure 4. Top 10 countries contributing to research on technology integration in physics education for SDG 4

The analysis of publication sources identified the ten most influential journals contributing to research on technology integration in physics education related to SDG 4, while also examining journal quartile rankings to assess the academic impact and quality of research dissemination. The results show that several leading sources are classified as Q1 and Q2 journals, which are known for their high academic impact and rigorous peer-review processes, indicating that research in this field is increasingly recognized within the international academic community. Overall, the distribution of publications across higher-quartile journals reflects the growing maturity of this research area and its relevance to global educational challenges, particularly in improving the quality of education as emphasized in SDG 4.

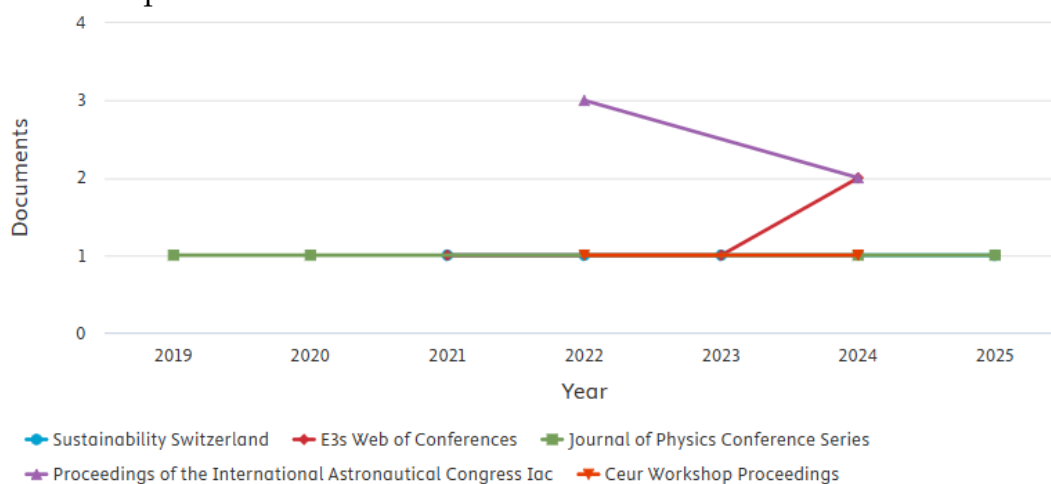


Figure 5. Top 10 publication sources and their journal quartiles

Keyword mapping was conducted using the search combination “technology AND physics AND SDGs OR SDG OR (sustainable AND development AND goal)” to identify thematic relationships and research clusters. The network visualization reveals five major clusters representing the main research directions in technology integration within physics education under the SDG framework. Cluster 1 (51 items) is primarily associated with the keyword *sustainable development goals*, Cluster 2 (50 items) with *sustainable development*, Cluster 3 (45 items) with *education*, Cluster 4 (42 items) with *engineering education* and *students*, and Cluster 5 (41 items) with *technology* as a dominant theme. Overall, these clusters demonstrate the multidisciplinary nature of the field by integrating themes of sustainability, educational innovation, technological advancement, and student learning processes, while also highlighting *sustainable development* as the central concept and emphasizing the strong alignment between technological innovation in physics education and the global agenda of SDG 4.

technology into physics education. In addition, Sustainable Development Goals (139) and (130) emphasize their strong connection to the global SDGs agenda. Meanwhile, machine learning (117) points to a growing trend of adopting artificial intelligence-based technologies to enhance the quality of learning. These findings suggest that research remains largely focused on sustainable development, but there is a noticeable shift toward the use of innovative technologies such as AI.

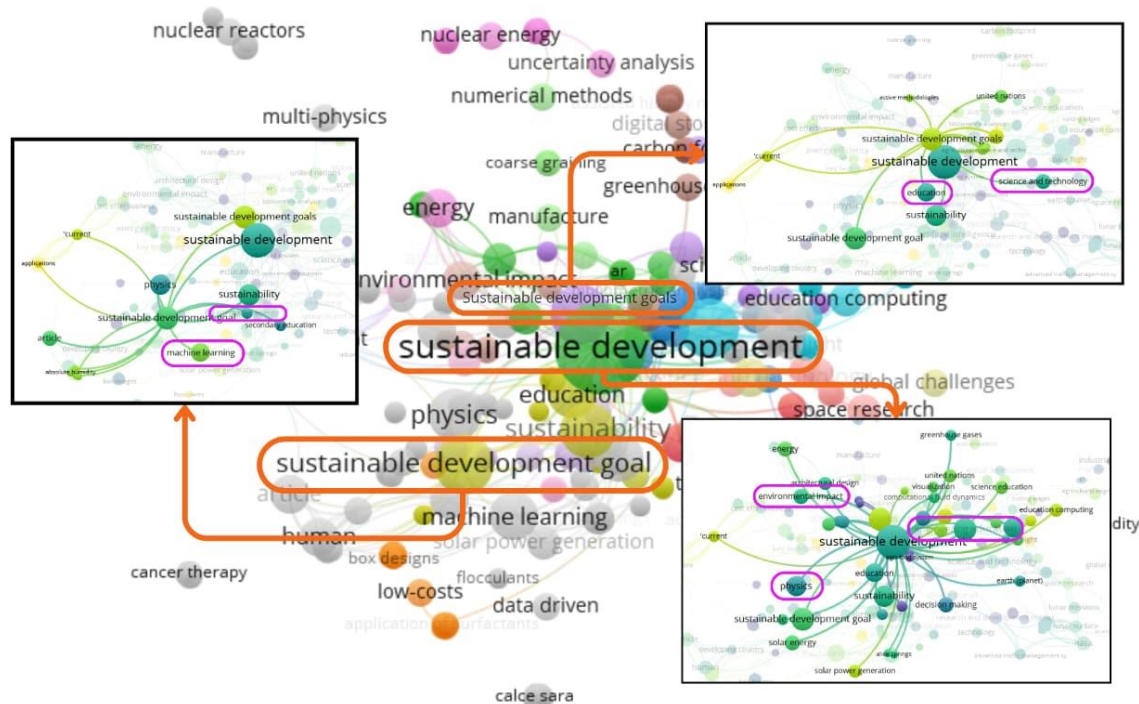


Figure 7. Keyword branches related to SDG 4

The keyword mapping shows that the terms *education*, *physics*, *sustainability*, and the *Sustainable Development Goal* function as central nodes in the research network, indicating that many studies focus on strengthening sustainable quality education through technology-enhanced physics learning. Additional keywords such as *education computing*, *active methodologies*, *augmented reality*, *machine learning*, and *data-driven learning* reveal a clear trend toward integrating digital technologies into physics education. Moreover, the presence of terms like *green development*, *renewable energy*, and *environmental impact* suggests that physics education research is increasingly connected with broader global sustainability challenges, including clean energy and climate change, indicating that this field contributes not only to SDG 4 but also supports other sustainability agendas, such as SDG 7, related to affordable and clean energy.

Table 3. Overview of most cited papers technology in physics learning for SDGs 4

Author (s)	Citation; SJR	Research Findings and Recommendations
Salwan Tajjour & Shyam Singh Chandel (2023)	90; 1,606 (Q1)	This study shows that conventional microgrids still face challenges from renewable energy intermittency and limited energy management systems. It recommends

Author (s)	Citation; SJR	Research Findings and Recommendations
Bronte Tilbrook et al (2019)	62; 0,931 (Q1)	developing an AI-driven, adaptive management system that integrates these technologies while addressing cost, scalability, and connectivity. This approach is expected to optimize next generation microgrid implementation in support of SDG 7, SDG 11, and SDG 13.
Weijie Zhao (2022)	56; 2,903 (Q1)	This study notes sensor limitations, scarce coastal-polar data, and unequal monitoring capacity in ocean acidification. It recommends affordable sensors, regional hubs, integrated chemical-biological frameworks, and stronger multidisciplinary coordination to support SDG 14.3 and coastal resilience.
Samuel Chukwujindu Nwokolo et al (2023)	50; 0,857 (Q1)	This study underscores the need for greater research and investment in renewable energy, affordable storage, green hydrogen, low-carbon transport, and CCUS. It recommends advancing energy transition through integrated storage, circular and hydrogen-based industries, and expanded carbon sinks, integrated by cross-sectoral approaches and adaptive local policies to accelerate the green industrial revolution, achieve the 2060 carbon-neutral target, and strengthen global ecological resilience.
Agariadne Dwinggo Samala et al (2023)	44; 0,484 (Q2)	This research needs funding for developing and validating a hybrid physics-based ML-GPM model, multisite testing, and global climate data access. It recommends optimizing efficiency, comparing PV sites and technologies, assessing long-term climate impacts, and integrating findings into sustainable energy planning through multidisciplinary collaboration.
This study requires funding for infrastructure, databases, and international collaboration, with future research recommended on MR exploration, pedagogy, cross-country comparisons, long-term evaluations, and integrating technology with teacher competencies.		

Discussion

The growing number of publications between 2016 and 2025 indicates that technology integration has become a central focus in physics education research. This trend reflects broader transformations in educational systems driven by rapid digital innovation and the expansion of technology-integrated learning environments. In physics education, technology plays a crucial role because many physical concepts are abstract and require visualization, simulation, and interactive representations to support conceptual understanding. Previous studies have shown that digital tools such as simulations,

virtual laboratories, and interactive platforms can enhance student engagement and improve conceptual learning outcomes in physics (Wahidin et al., 2025).

A notable acceleration in publication growth after 2021 can be associated with the rapid expansion of digital learning during the COVID-19 pandemic. The global transition to online and hybrid learning environments required educational institutions to adopt digital technologies to sustain teaching and learning processes. Consistent with this trend, Tan (2024) reported a substantial increase in technology-related educational research following the widespread implementation of remote learning. The keyword patterns identified in this study further reinforce this trend. Terms such as *machine learning*, *augmented reality*, and *active methodologies* frequently appear in the research network, indicating a shift toward more adaptive, immersive, and student-centered learning environments.

The bibliometric findings also reveal that conference publications remain dominant in this research field. This suggests that studies on technology integration in physics education are still evolving, with many works initially presented at conferences before being developed into journal articles. Conferences, therefore, serve as important venues for sharing emerging ideas and testing new educational technologies. However, the relatively limited number of books and book chapters indicates that the theoretical foundations of this research area have not yet been fully consolidated, highlighting the need for stronger theoretical synthesis in future studies.

Another important finding is the significant contribution from both developed and developing countries, including Indonesia, India, and Malaysia. This pattern may be related to national initiatives promoting the integration of digital technologies in science education. In many developing countries, technology-based learning is considered an effective strategy to overcome limitations in laboratory infrastructure, teaching resources, and access to quality educational materials through virtual experiments, simulations, and open educational resources.

Keyword co-occurrence analysis further shows that research on technology in physics education is increasingly linked with broader sustainability challenges. The presence of terms such as *renewable energy*, *climate change*, and *sustainable development* alongside educational technology keywords indicates a growing interdisciplinary orientation that connects physics learning to real-world global issues. This trend aligns with Sustainable Development Goal 4, which emphasizes inclusive and quality education as a foundation for sustainable development.

From a pedagogical perspective, the technological innovations identified in this bibliometric mapping support more interactive and inquiry-oriented learning environments. Digital simulations and virtual laboratories allow students to explore physical phenomena that are difficult to observe directly in conventional laboratory settings, while immersive technologies such as augmented reality enhance conceptual visualization and spatial understanding of complex physical systems.

Overall, the findings demonstrate that research on technology-enhanced physics education is expanding rapidly and becoming increasingly interdisciplinary.

Nevertheless, several research gaps remain. Future studies should not only explore emerging technologies but also evaluate their pedagogical effectiveness, accessibility, and long-term impact on student learning outcomes, particularly regarding the integration of artificial intelligence, immersive visualization technologies, and data-driven learning systems in physics education. This study contributes to the literature by providing a comprehensive bibliometric mapping of technology integration in physics education, highlighting emerging research trends, dominant thematic areas, and global collaboration patterns that can guide future research and the development of more effective technology-integrated physics learning.

CONCLUSION

Fundamental Finding: This study reveals that the integration of technology into physics education has experienced significant growth between 2016 and 2025, with a marked surge in publications after 2021, highlighting the growing global attention to SDG 4. The keyword trends indicate an increasing use of advanced technologies such as augmented reality and machine learning, underscoring the strategic role of technology in enhancing the quality and relevance of physics education. **Implications:** The findings carry implications across three key dimensions: (1) educators are encouraged to design more interactive and contextualized learning environments; (2) policymakers can utilize the publication mapping as a reference point for determining research priorities; and (3) the global academic community may leverage the integration of technology in physics education as a pathway to connect learning with broader sustainability agendas. **Limitations:** The scope of this study is limited to the Scopus database and therefore does not capture all potentially relevant publications. In addition, bibliometric analysis remains largely descriptive and has not yet assessed the empirical effectiveness of technology implementation in practice. The 2016–2025 timeframe also constrains the ability to observe long-term trends. **Future Research:** Future research should be directed toward cross-country comparative studies, the development of AI- and AR-based pedagogical models for personalized learning, and longitudinal evaluations that assess the long-term impact of technology on learning outcomes, 21st-century skills, and its tangible contributions to the achievement of SDG 4.

AUTHOR CONTRIBUTION

Sherlynggar Anugrah lead the overall research process, including formulating the research focus, designing the bibliometric–SLR integration procedure, conducting data extraction from Scopus, managing PRISMA screening, and drafting the initial manuscript. **Wildan Khusni Mubarok** contributed to data preprocessing, the execution of Bibliometrix and VOSviewer analyses, interpretation of visualizations, and refinement of the methodological explanations. **Wildan Fitroni** was responsible for constructing tables and figures, validating statistical outputs, ensuring consistency between the results and the discussion, and assisting with manuscript revision. **Khoirun Nisa'** contributed to strengthening the theoretical foundation related to SDG 4, reviewing the discussion

alignment with sustainability perspectives, and providing critical revisions to enhance academic rigor and coherence of the final manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest.

ETHICAL COMPLIANCE STATEMENTS

This study adheres to the ethical standards of bibliometric and systematic literature review research. All data were obtained legally from the Scopus database, analyzed using established protocols, and reported transparently following the PRISMA workflow. No part of this work involved human participants, experimental interventions, or sensitive data. The authors affirm that the manuscript is original, free from plagiarism, and has not been submitted to or published in any other venue.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors declare that the research design, data collection, PRISMA screening, bibliometric processing (including VOSviewer and Bibliometrix), interpretation of findings, and manuscript preparation were carried out manually by the authors. No artificial intelligence (AI) or automatic text-generation tools were used in drafting, analyzing, or editing the scientific content of this article. Full responsibility for the accuracy, originality, and integrity of the manuscript rests solely with the authors.

REFERENCES

- Apata, O. E., Ajose, S. T., Apata, B. O., Olaitan, G. I., Oyewole, P. O., Ogunwale, O. M., Oladipo, E. T., Oyeniran, D. O., Awoyemi, I. D., Ajobiewe, J. O., Ajamobe, J. O., Appiah, I., Fakhrou, A. A., & Feyijimi, T. (2025). Artificial intelligence in higher education: a systematic review of contributions to SDG 4 (quality education) and SDG 10 (reduced inequality). *International Journal of Educational Management*, 39(2), 1-18. <https://doi.org/10.1108/IJEM-12-2024-0856>
- Awwalina, D. P., Dawana, I. R., Dwikoranto, D., & Rizki, I. A. (2025). Efektivitas pendidikan STEAM dalam pembelajaran fisika dan dampaknya dalam mendukung SDGs. *Jurnal Studi Terkini SDGs*, 1(1), 1-19. <https://doi.org/10.63230/jocsis.1.1.8>
- Bircan, T., & Salah, A. A. A. (2022). A bibliometric analysis of the use of artificial intelligence technologies for social sciences. *Mathematics*, 10(23), 4398. <https://doi.org/10.3390/math10234398>
- Bitzenbauer, P. (2021). Quantum physics education research over the last two decades: A bibliometric analysis. *Education Sciences*, 11(11), 699. <https://doi.org/10.3390/educsci11110699>
- Cloete, D. N., Shoko, C., Dube, T., & Clarke, S. (2024). Remote sensing-based land use land cover classification for the Heuningnes Catchment, Cape Agulhas, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 134, 103559. <https://doi.org/10.1016/j.pce.2024.103559>
- Dewi, C. A., & Rahayu, S. (2023). Implementation of case-based learning in science education: a systematic review. *Journal of Turkish Science Education*, 20(4), 729-749. <https://doi.org/10.36681/tused.2023.041>

- Ferrer-Estévez, M., & Chalmeta, R. (2021). Integrating sustainable development goals in educational institutions. *The International Journal of Management Education*, 19(2), 100494. <https://doi.org/10.1016/j.ijme.2021.100494>
- Hölscher, K., Wittmayer, J. M., Hirschnitz-Garbers, M., Olfert, A., Walther, J., Schiller, G., & Brunnow, B. (2021). Transforming science and society? Methodological lessons from and for transformation research. *Research Evaluation*, 30(1), 73-89. <https://doi.org/10.1093/reseval/rvaa034>
- Jugembayeva, B., & Murzagaliyeva, A. (2022). Physics students' innovation readiness for digital learning within the university 4.0 model: Essential scientific and pedagogical elements that cause the educational format to evolve in the context of advanced technology trends. *Sustainability*, 15(1), 233. <https://doi.org/10.3390/su15010233>
- Karuppiah, K., Sankaranarayanan, B., & Ali, S. M. (2023). A systematic review of sustainable business models: Opportunities, challenges, and future research directions. *Decision Analytics Journal*, 8, 100272. <https://doi.org/10.1016/j.dajour.2023.100272>
- Khanra, S., Kaur, P., Joseph, R. P., Malik, A., & Dhir, A. (2022). A resource-based view of green innovation as a strategic firm resource: Present status and future directions. *Business Strategy and the Environment*, 31(4), 1395-1413. <https://doi.org/10.1002/bse.2961>
- Lim, C. K., Haufiku, M. S., Tan, K. L., Farid Ahmed, M., & Ng, T. F. (2022). Systematic review of education sustainable development in higher education institutions. *Sustainability*, 14(20), 13241. <https://doi.org/10.3390/su142013241>
- Lintangesukmanjaya, R. T., Dwikoranto, D., Awwalina, D. P., Setiani, R., & Bergsma, L. N. (2025). Potential study SDGs 4 of deep learning approaches to improve problem solving with machine learning innovation: Empirical and bibliometric analysis. *E3S Web of Conferences*, 640(9), 02018. <https://doi.org/10.1051/e3sconf/202564002018>
- Lyu, H., Lim, J. Y., Zhang, Q., Senadheera, S. S., Zhang, C., Huang, Q., & Ok, Y. S. (2024). Conversion of organic solid waste into energy and functional materials using biochar catalyst: Bibliometric analysis, research progress, and directions. *Applied Catalysis: Environmental*, 340, 123223. <https://doi.org/10.1016/j.apcatb.2023.123223>
- Lyu, H., Matsuura, S., Wagai, R., Yasuno, H., Tanaka, H., & Sugihara, S. (2025). Plant residue quality regulates mineral-associated organic matter formation rate and pathway in converted upland soil. *Environmental Research*, 122158. <https://doi.org/10.1016/j.envres.2025.122158>
- Masuda, H., Kawakubo, S., Okitasari, M., & Morita, K. (2022). Exploring the role of local governments as intermediaries to facilitate partnerships for the Sustainable Development Goals. *Sustainable Cities and Society*, 82, 103883. <https://doi.org/10.1016/j.scs.2022.103883>
- 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>
- Payne-Gifford, S., Whatford, L., Tak, M., Van Winden, S., & Barling, D. (2022). Conceptualising disruptions in British beef and sheep supply chains during the COVID-19 crisis. *Sustainability*, 14(3), 1201. <https://doi.org/10.3390/su14031201>
- Pham, H. T., Vu, T. C., Nguyen, L. T., Vu, N. T. T., Nguyen, T. C., Pham, H. H. T., Lai, L. P., Le, H. C. T., & Ngo, C. H. (2023). Professional development for science teachers:

- A bibliometric analysis from 2001 to 2021. *Eurasia Journal of Mathematics, Science and Technology Education*, 19(5), em2260. <https://doi.org/10.29333/ejmste/13153>
- Prahani, B. K., Dawana, I. R., Jatmiko, B., & Amelia, T. (2023). Research trend of big data in education during the last 10 years. *International Journal of Emerging Technologies in Learning*, 18(10). <https://doi.org/10.3991/ijet.v18i10.38453>
- Prieto-Jiménez, E., López-Catalán, L., López-Catalán, B., & Domínguez-Fernández, G. (2021). Sustainable development goals and education: A bibliometric mapping analysis. *Sustainability*, 13(4), 2126. <https://doi.org/10.3390/su13042126>
- Rad, D., Redeş, A., Roman, A., Ignat, S., Lile, R., Demeter, E., ... & Rad, G. (2022). Pathways to inclusive and equitable quality early childhood education for achieving SDG4 goal—a scoping review. *Frontiers in psychology*, 13, 955833. <https://doi.org/10.3389/fpsyg.2022.955833>
- Saini, M., Sengupta, E., Singh, M., Singh, H., & Singh, J. (2023). Sustainable Development Goal for Quality Education (SDG 4): A study on SDG 4 to extract the pattern of association among the indicators of SDG 4 employing a genetic algorithm. *Education and Information Technologies*, 28(2), 2031-2069. <https://doi.org/10.1007/s10639-022-11265-4>
- 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). <https://doi.org/10.3991/ijep.v13i2.35965>
- Serafini, P. G., de Moura, J. M., de Almeida, M. R., & de Rezende, J. F. D. (2022). Sustainable development goals in higher education institutions: a systematic literature review. *Journal of Cleaner Production*, 370, 133473. <https://doi.org/10.1016/j.jclepro.2022.133473>
- Singh, V. K, Singh, P., Karmakar, M., Leta, J., & Mayr, P. (2021). Journal coverage of web of science, scopus, and dimensions: a comparative analysis. *Scientometrics*, 126 (6), 5113-5142. <https://doi.org/10.1007/s11192-021-03948-5>
- Sriadhi, S., Hamid, A., Sitompul, H., & Restu, R. (2022). Effectiveness of augmented reality-based learning media for engineering-physics teaching. *International Journal of Emerging Technologies in Learning (IJET)*, 17(5), 281-293. <https://doi.org/10.3991/ijet.v17i05.28613>
- Tajjour, S., & Chandel, S. S. (2023). A comprehensive review on sustainable energy management systems for optimal operation of future-generation of solar microgrids. *Sustainable Energy Technologies and Assessments*, 58, 103377. <https://doi.org/10.1016/j.seta.2023.103377>
- Tan, Y. (2024). A bibliometric analysis of scholarly literature related to digital literacy in higher education during the pandemic period. *Cogent Education*, 11(1), 2341587. <https://doi.org/10.1080/2331186X.2024.2341587>
- Tilbrook, B., Jewett, E. B., DeGrandpre, M. D., Hernandez-Ayon, J. M., Feely, R. A., Gledhill, D. K., & Telszewski, M. (2019). An enhanced ocean acidification observing network: from people to technology to data synthesis and information exchange. *Frontiers in Marine Science*, 6, 337. <https://doi.org/10.3389/fmars.2019.00337>
- Wahab, M. N. N. D., Prahani, B. K., Haryono, H. E., & Jatmiko, B. (2025). Research trends of student scientific literacy assessment to support quality education. *Journal of Lifestyle and SDGs Review*, 5(1), e03916-e03916. <https://doi.org/10.47172/2965-730X.SDGsReview.v5.n01.pe03916>

- Wahidin, W., Gutierrez, G., Osman, K., Akkapin, S., & Tan, M. L. T. (2025). Digital simulations in science learning: A student perspective on interactive, engagement, conceptual understanding, and learning satisfaction. *International Journal of Educational Qualitative Quantitative Research*, 4(1), 36-46. <https://doi.org/10.58418/ijeqqr.v4i1.138>
- Wang, X. L. (2023). Meta-governance, uncertainty and self-organization in corporatist social service sectors: The case of Hong Kong. *International Review of Administrative Sciences*, 89(4), 1186-1202. <https://doi.org/10.1177/00208523221147617>
- Wilczyński, P. L. (2021). A comparison of the general knowledge and skills displayed by students participating in international geopolitical competitions. *Education Sciences*, 10(9), 255. <https://doi.org/10.3390/educsci10090255>
- Xu, F., Ou, G., Ma, T., & Wang, X. (2021). Konsistensi dampak pracetak dan publikasi jurnalnya. *Jurnal Informetrika*, 15(2), 101153. <https://doi.org/10.1016/j.joi.2021.101153>
- Zhang, L., Ling, J., & Lin, M. (2022). Artificial intelligence in renewable energy: A comprehensive bibliometric analysis. *Energy Reports*, 8, 14072-14088. <https://doi.org/10.1016/j.egyr.2022.10.347>
- Zhang, Y., Duan, Z., Shu, P., & Deng, J. (2023). Exploring acceptable risk in engineering and operations research and management science by bibliometric analysis. *Risk Analysis*, 43(8), 1539-1556. <https://doi.org/10.1111/risa.14049>
- Zhao, W. (2022). China's goal of achieving carbon neutrality before 2060: experts explain how. *National Science Review*, 9(8), 115. <https://doi.org/10.1093/nsr/nwac115>

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