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Artificial Intelligence in Physics Learning for Education for Sustainable Development: A Bibliometric Analysis

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ABSTRACT

Objective: *This study aims to map the global research landscape on Artificial Intelligence (AI) in physics education within the framework of Education for Sustainable Development (ESD) using a bibliometric approach. The objective is to identify publication trends, key contributors, collaborative networks, and emerging themes that define the development of this research domain.* ***Method:*** *The analysis was based on 4,814 documents retrieved from the Scopus database for the period 2015–2025. Data preprocessing included deduplication and keyword harmonization. Bibliometric analysis was conducted using performance indicators (publication output, influential authors, journals, countries, institutions) and science mapping (co-authorship, co-occurrence, co-citation) with VOSviewer and Bibliometrix.* ***Results:*** *Findings reveal three phases of publication dynamics: initial emergence (2015–2018), growth (2019–2021), and accelerated expansion (2022–2024), with a peak in 2024. The United States dominates global output, followed by China and Indonesia. Physics-focused journals such as Physical Review Physics Education Research and Journal of Physics: Conference Series serve as major outlets. Co-authorship networks show a core cluster in Europe and North America, while Asian and Global South researchers are increasingly active. Thematic mapping highlights clusters on AI-enabled assessment, machine learning, Large Language Models (LLMs), and sustainability-oriented physics education.* ***Novelty:*** *This paper provides a systematic overview of the intellectual structure and thematic evolution of AI-based physics education for ESD. It identifies gaps, including limited cross-country collaboration, low experimental validation, and uneven global participation, while highlighting opportunities for ethical, inclusive, and sustainability-aligned AI integration in future physics learning.*

INTRODUCTION

Physics education plays a central role in shaping scientific literacy, critical thinking skills, and the younger generation's readiness to address the global challenges of the 21st century. However, physics learning often faces obstacles due to its abstract nature, low student engagement, and limitations in connecting theory with real-world applications (Prayogi & Verawati, 2024; Alhusni et al., 2025). Along with digital transformation, artificial intelligence (AI) is increasingly being adopted in education. AI enables personalized learning, automated feedback, data-driven analytics, and even the provision of adaptive brilliant tutors (Zawacki-Richter et al., 2019; Donthu et al., 2021). In the context of physics education, the application of AI includes the use of machine learning to predict student performance, natural language processing for open-ended response analysis, and large language models such as ChatGPT for formative assessment and conceptual feedback (Kortemeyer, 2023; Yeadon & Hardy, 2023; Wan & Chen, 2024). At the same time, the international community is promoting the Education for Sustainable Development (ESD) agenda, integrated into the Sustainable Development Goals (SDGs). ESD emphasizes the development of sustainability competencies such as systems thinking, anticipatory thinking, collaborative thinking, and normative thinking, which are very important for science education (Brundiers et al., 2021). The integration of AI in physics education has the potential to reinforce these goals through interactive simulations, data-based projects, and contextual learning about renewable energy and environmental issues (Rodríguez-Abitia & García-Sánchez, 2021; Prayogi & Verawati, 2024). Thus, AI not only serves as a pedagogical innovation but also as a strategic means to build sustainability awareness in physics learning (Aoulkadi et al., 2025).

Despite its great potential, AI in education still poses serious challenges. The literature highlights the risks of algorithmic bias, data privacy issues, the impact of computational energy, and access inequalities between developed and developing countries (Vinuesa et al., 2020; Goralski & Tan, 2023; Porayska-Pomsta et al., 2024). Other research confirms that while AI can accelerate the achievement of SDGs, this technology also has the potential to widen social gaps if not regulated ethically (Selwyn, 2019; Reich, 2020). Therefore, the use of AI in the classroom must be inclusive, responsible, and in line with the principles of sustainability (UNESCO, 2021).

A growing body of empirical studies demonstrates that AI is beginning to exert a positive influence on physics learning. For instance, Henze et al. (2024) showed that AI-supported experimental data analysis not only enhances student motivation but also reduces stress levels in laboratory activities. Similarly, Yeadon and Hardy (2023) reported that large language models can produce conceptual answers comparable to, or even surpassing, those of students. However, these models occasionally generate incorrect responses that appear convincing. At the same time, Mahligawati et al. (2023) stressed that the integration of AI into physics education remains hampered by infrastructural constraints and limited teacher preparedness. Recent work on adoption perspectives also indicates that physics lecturers follow a diffusion-of-innovation trajectory, progressing from initial awareness to actual classroom implementation (Physics Teaching Research, 2025). Comparable findings are also reported in systematic reviews, which highlight both opportunities and persistent challenges of AI in higher education, particularly regarding ethical concerns and educators' readiness (Zawacki-Richter et al., 2019; Donthu et al., 2021).

Despite these promising developments, current studies primarily focus on classroom practices, small-scale experiments, or specific technological applications, leaving significant gaps in the literature. First, there is a lack of comprehensive mapping of how AI in physics education aligns with the broader agenda of Education for Sustainable Development (ESD), particularly in fostering competencies such as systems thinking and sustainability literacy. Second, while evidence exists on the effectiveness of AI tools in improving student performance, few studies systematically investigate global collaboration patterns, thematic clusters, and the intellectual structure underlying this emerging field. Third, the ethical, environmental, and inclusivity dimensions of AI adoption in physics classrooms remain underexplored, even though these are critical for ensuring that technological integration supports, rather than undermines, the Sustainable Development Goals. Addressing these gaps requires a bibliometric approach capable of capturing the dynamics, knowledge base, and future research directions of AI in physics learning for ESD.

Beyond pedagogical aspects, research developments also highlight methodological dimensions. Bibliometric studies provide an appropriate approach to mapping the evolution of research on AI in education, including physics and ESD (Akhmadieva et al., 2023; Sahar & Munawaroh, 2025). Through bibliometric analysis, publication trends, collaboration networks, and theme clusters can be identified, providing a comprehensive picture of research direction. Several studies show that although publications on AI and education are increasing rapidly, cross-country collaboration is still relatively limited (Larbi et al., 2025). Such studies are crucial because they can formulate a future research agenda that focuses not only on the effectiveness of technology but also on its implications for ethics, inclusivity, and educational sustainability.

Thus, the urgency of research at the intersection of AI, physics education, and ESD is increasing. A bibliometric study of publications over the past decade can provide a deeper understanding of the dynamics of research in this field. The results will not only strengthen theoretical contributions to the development of science but also provide practical recommendations for implementing AI that supports physics learning while aligning with global sustainable development goals.

RESEARCH METHOD

This study uses a bibliometric approach to map the development of research related to the use of Artificial Intelligence (AI) in physics education and its relationship with Education for Sustainable Development (ESD). The research data were obtained from the Scopus database, which was chosen for its wide coverage and metadata quality suitable for bibliometric analysis (Martín-Martín et al., 2021). The literature search was conducted using the keywords "artificial intelligence," "machine learning," "deep learning," and "physics education" across publications from 2015 to 2025, yielding 1,093 documents. The documents were then filtered to include only those relevant to sustainability—namely, Education for Sustainable Development (ESD) and sustainable development—reducing the total to 881. The next stage was eligibility selection, in which only English-language final versions of journal articles and conference proceedings were retained, resulting in 704 documents. After validation and duplication removal, 610 final documents were obtained for further analysis.

Data analysis was conducted using two main approaches. First, performance analysis was used to measure annual publication trends and the distribution of authors, journals, institutions, and countries. Second, science mapping was used to map the scientific structure through author collaboration networks (co-authorship), keyword interrelationships (co-occurrence), and inter-reference relationships (co-citation). The analysis was conducted using VOSviewer software and the R-based Bibliometrix package, which have proven effective for producing systematic, comprehensive bibliometric visualizations (Moral-Muñoz et al., 2020; Perianes-Rodriguez et al., 2020; Donthu et al., 2021). Using this method, the study provided a complete picture of publication trends, collaboration networks, and emerging themes in AI research for physics education oriented towards sustainability.

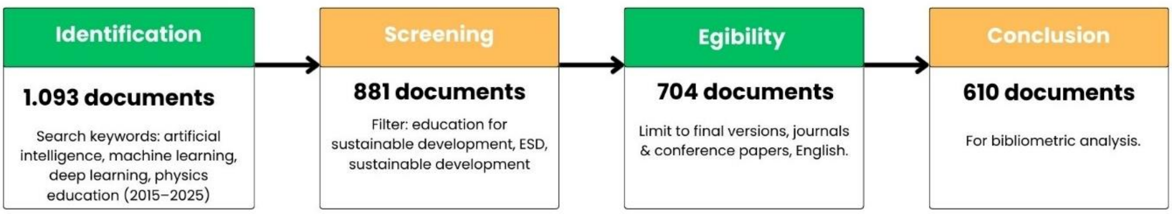

Figure 1. PRISMA flowchart of the process of identifying, screening, eligibility, and selection of research documents

RESULTS AND DISCUSSION

Results

An annual analysis of scientific production on Artificial Intelligence, Physics Education, and Education for Sustainable Development shows a consistent increase from 2015 to 2025. In the initial phase (2015–2017), the number of publications was still relatively low—below 40 per year—and showed an upward trend but was not yet stable. The year 2018 saw a decline, but since 2019, there has been an increase, with an average of 40–55 articles per year until 2021. A sharper increase occurred in 2022–2023, reaching more than 70 articles, before peaking in 2024 with more than 110 articles. In 2025, the number of publications declined, but it remains higher than during the early period of 2015–2019.

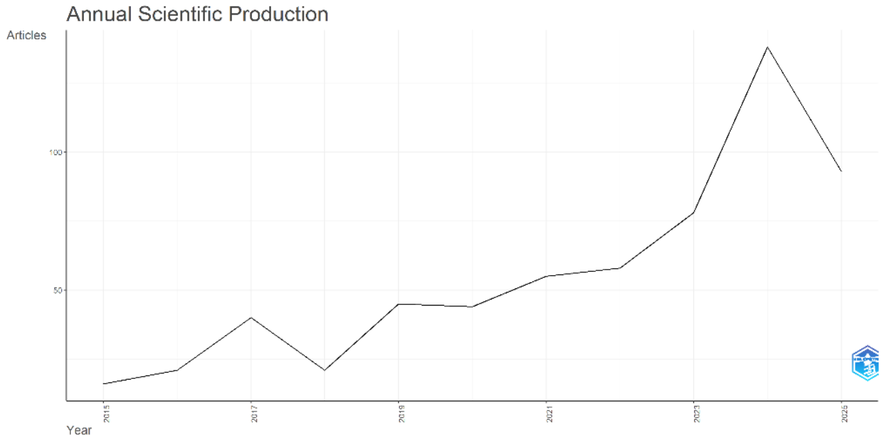

Figure 2. Annual scientific publication trends (2015–2025) on the themes of artificial intelligence, physics education, and education for sustainable development

The analysis of Sources' Local Impact by H index shows that several journals and proceedings played a dominant role in publications on Artificial Intelligence, Physics Education, and Education for Sustainable Development during 2015–2025, as shown in Figure 3. The source with the highest H-index value is recorded as "NA" (H = 11), most likely because some publications have not been fully classified in the Scopus database. In the following position, Physical Review Physics Education Research (PRPER) stands out with an H-index of 8, confirming its status as a leading journal in physics education. Three other journals — Computer Applications in Engineering Education, European Journal of Physics, and Journal of Physics: Conference Series — each recorded an H value of 5. Meanwhile, Journal of Science Education and Technology had H = 4, and several other sources were at a lower level (H = 3), including Academic Radiology, ASEE Annual Conference Proceedings, CEUR Workshop Proceedings, and Computers and Education: Artificial Intelligence.

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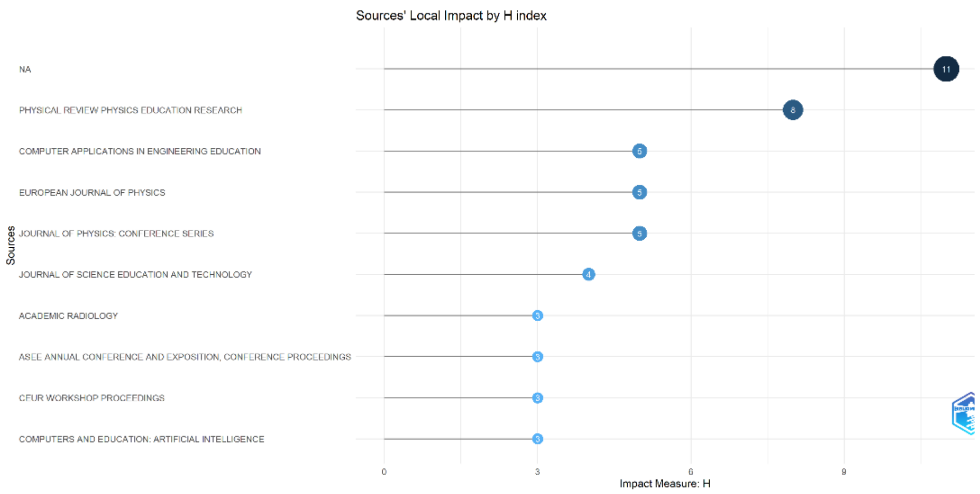

Figure 3. Distribution of local impact of publications based on H-index in research on artificial intelligence, physics education, and education for sustainable development (2015–2025)

Figure 4 illustrates the cumulative development of publications in five primary sources contributing to research on the themes of Artificial Intelligence, Physics Education, and Education for Sustainable Development in the period 2015–2025. Based on the trends observed, the Journal of Physics: Conference Series is the source with the highest publication output, recording consistent growth since 2018 and surpassing 35 publications in 2025. The next position is occupied by Physics Education, which shows a steady increase since 2019 and exceeds 25 publications in 2024, though it tends to stagnate thereafter. Physical Review Physics Education Research (PRPER) also shows positive growth, with a significant increase, especially after 2021, reaching nearly 20 publications in 2025. Meanwhile, the ASEE Annual Conference and Exposition Proceedings and Proceedings of SPIE record smaller contributions, each with fewer than 15 cumulative publications by 2025.

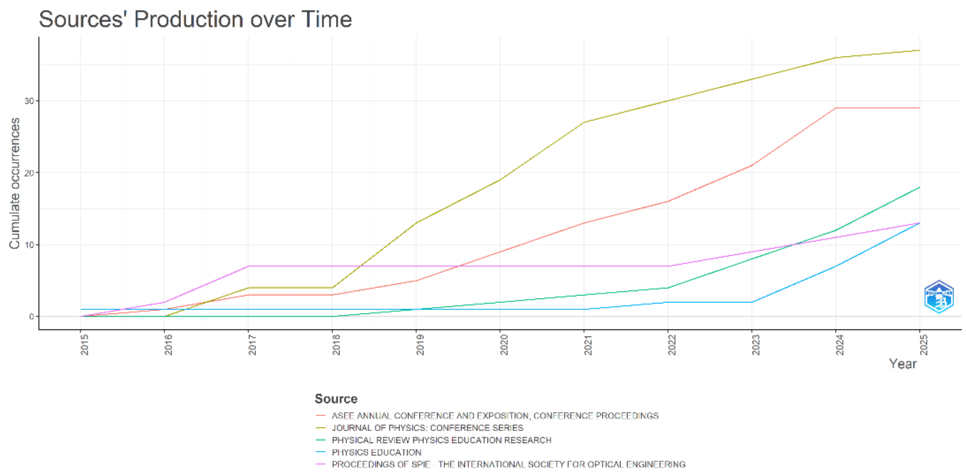

Figure 4. Cumulative production of publications from five primary sources (2015–2025)

Figure 5 shows the authors with the most publications on the topics of Artificial Intelligence, Physics Education, and Education for Sustainable Development. It can be seen that Li Y and Wulff P are in the top positions with six documents each. The following positions are occupied by Borowski A and Nowak A, both of whom have published five papers. Next, there is a group of authors with four publications: Caballero MD, Chen Z, Dominguez A, Fussell RK, Holmes NG, and Mientus L. This distribution shows a combination of highly productive researchers and authors with moderate contributions, forming an active research network in this field.

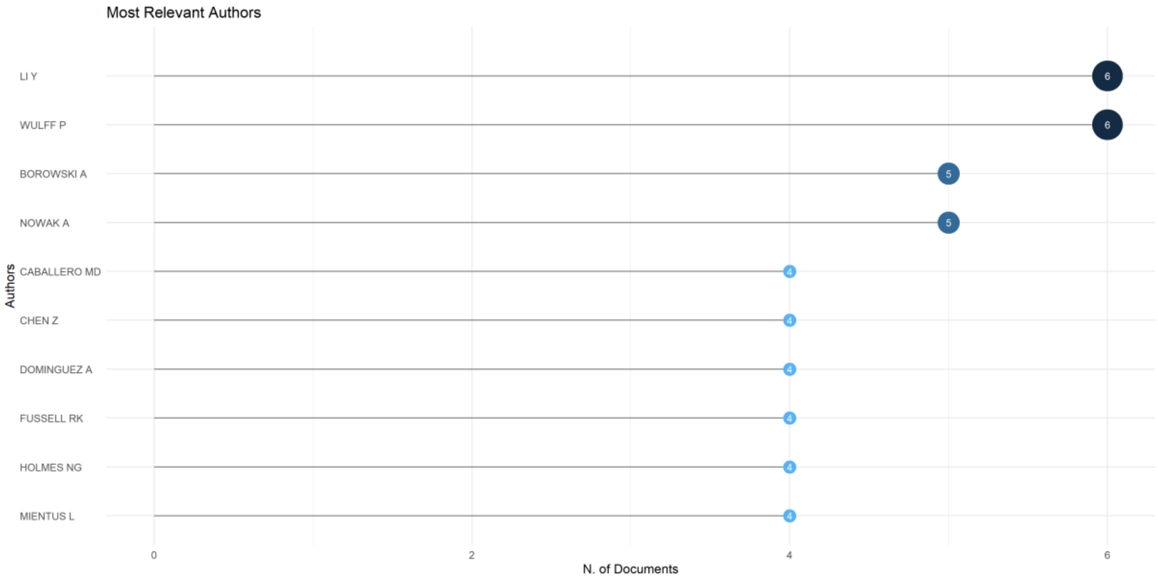

Figure 5. Most relevant authors based on the number of publications on the themes of Artificial Intelligence, Physics Education, and Education for Sustainable Development (2015–2025)

Figure 6 shows the publication dynamics of top authors in research on Artificial Intelligence, Physics Education, and Education for Sustainable Development between 2017 and 2025. Authors Li Y and Wulff P appear to be the most consistent in their productivity, with publications distributed over several years and a surge in 2023–2025. Authors such as Borowski A and Nowak A also show a similar trend, active since 2020 and steadily adding publications until 2023. Meanwhile, authors Caballero, MD, Chen Z, and Dominguez A have made fairly consistent contributions since 2019, with each publishing several papers through 2024. Other authors, such as Fussell RK, Holmes NG, and Mientus L, tend to be more active in the 2021–2023 period. Overall, this graph shows that publications began to increase significantly in 2019, with several authors reaching peak activity in 2023.

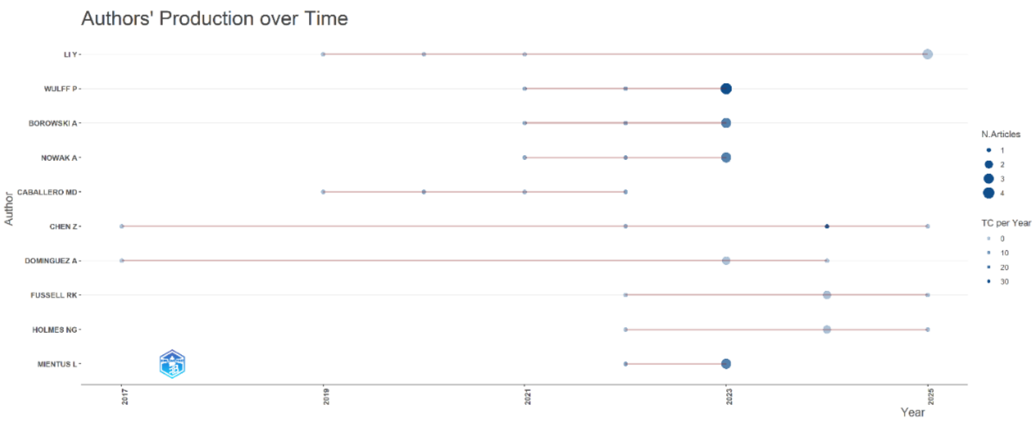

Figure 6. Top authors' productivity year by year (2017–2025)

Figure 7 shows the authors with the highest local impact in research on Artificial Intelligence, Physics Education, and Education for Sustainable Development during 2015–2025. Wulff P ranks highest, with an H-index of 5, indicating stronger citation consistency than other authors. The following positions are occupied by Borowski A, Caballero MD, and Nowak A, each with an H-index of 4. In addition, there is a group of authors with an H-index of 3, namely Aiken JM, Chen Z, Corbi A, Mientus L, Paul A, and Shute VJ. This distribution shows a concentration of core authors with a reasonably high citation impact, as well as a group of authors who, although less productive than the core group, still make a significant contribution to building the literature base in this field.

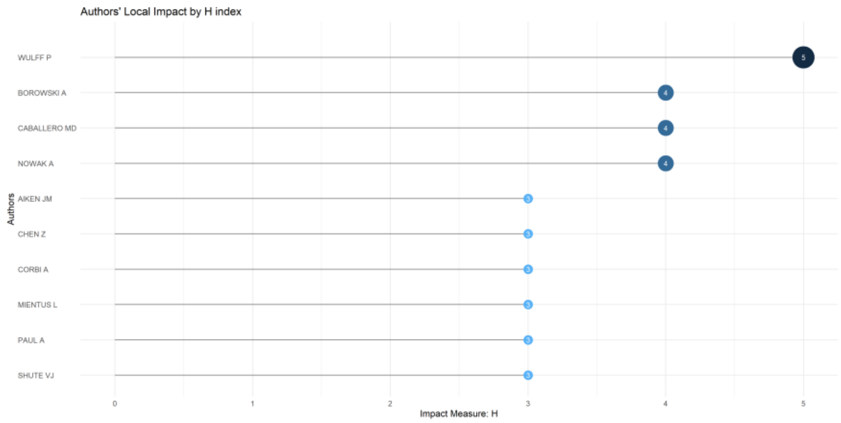

Figure 7. The local impact of authors based on the H-index in research

Figure 8 shows the institutions with the highest publication contributions on the themes of Artificial Intelligence, Physics Education, and Education for Sustainable Development for the period 2015–2025. Purdue University ranks first with 12 articles, followed closely by the State University of Jakarta (UNJ) with 11 articles. Other institutions that also made significant contributions, with eight articles each, are the College of Engineering, Columbia University, Karlsruher Institut für Technologie (KIT), University of Texas at Dallas, and Universitetet i Oslo. Meanwhile, Michigan State University, Universidad de Zaragoza, and Universität Potsdam are slightly behind with seven articles each.

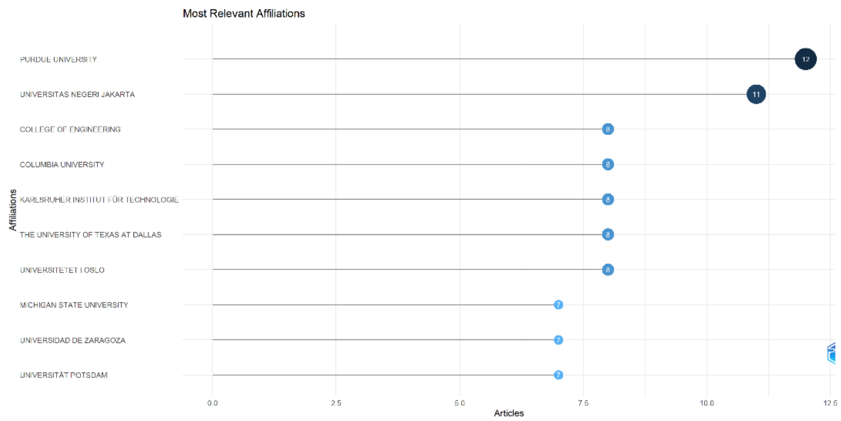

Figure 8. Institutions with the most publications

Figure 9 shows the dynamics of institutional contributions to publications related to Artificial Intelligence, Physics Education, and Education for Sustainable Development for the period 2015–2025. Purdue University has shown a consistent publication trend since the beginning, with sustained growth reaching eight articles in 2023 and remaining stable until 2025. Meanwhile, Jakarta State University (UNJ) has experienced rapid growth since 2019, with a significant surge after 2021, reaching its highest position in 2024–2025 with 12 articles. The University of Texas at Dallas also recorded a sharp increase since 2020, matching UNJ in 2024–2025. Other institutions such as Columbia University, Karlsruher Institut für Technologie (KIT), and Universitetet i Oslo show more moderate but stable growth, especially since 2019. The College of Engineering had a faster initial contribution, but its growth is relatively flat compared to other institutions.

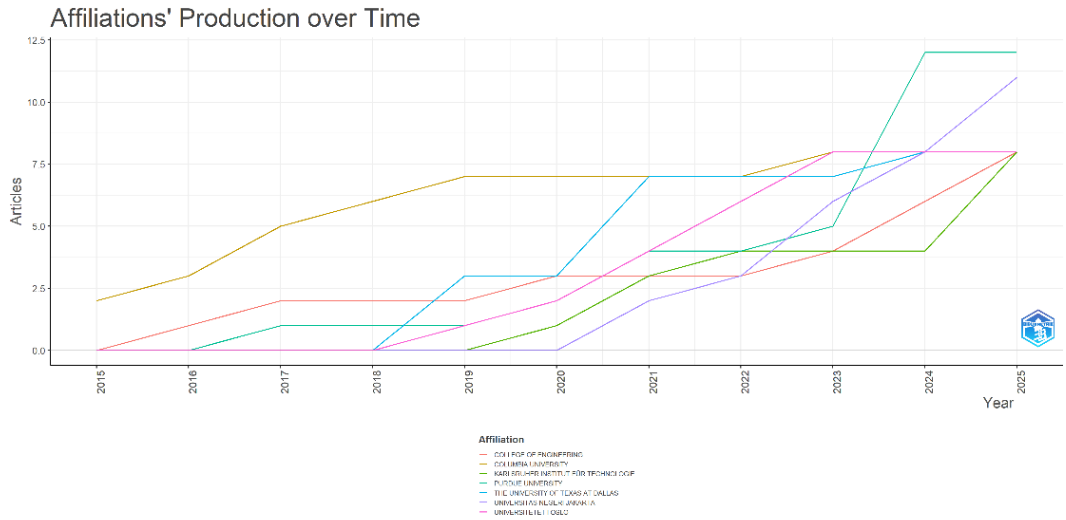

Figure 9. Annual publication output by institutional affiliation (2015–2025)

Figure 10 shows the distribution of publications based on the country of affiliation of the corresponding author in research on Artificial Intelligence, Physics Education, and Education for Sustainable Development for the period 2015–2025. The United States (USA) occupies a dominant position with nearly 150 documents, far surpassing other countries. China ranks second, followed by Indonesia in third place. European countries such as Germany, Spain, Italy, the United Kingdom, and Sweden made significant contributions, although their volumes were lower than those of the US and China. Meanwhile, other Asian countries such as India and South Korea, as well as Latin American countries such as Mexico, Brazil, and Chile, also contributed moderately. In addition to domestic publications (SCP = Single Country Publications), there are also contributions from international collaborative publications (MCP = Multiple Country Publications), especially in large countries such as China, Canada, Germany, and Spain, which show a high level of involvement in global collaboration.

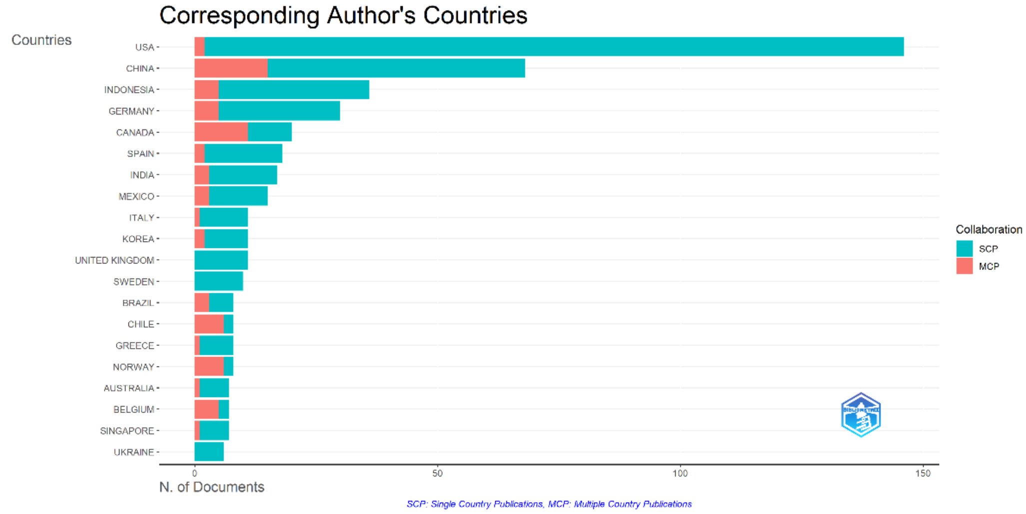

Figure 10. Distribution of countries of correspondence authors by number of publications (2015–2025)

Figure 11 shows the global distribution of scientific publications related to Artificial Intelligence, Physics Education, and Education for Sustainable Development for the period 2015–2025. The countries with the most dominant contributions are shown in dark blue, namely the United States, followed by China, Indonesia, Germany, Canada, and several European countries, such as Spain, Italy, and the United Kingdom. Other Asian countries, such as India, South Korea, and Singapore, are also active, although their volumes are relatively lower. In Latin America, contributions come from Brazil, Mexico, and Chile, while in Oceania, Australia is an important contributor. Most African countries are still grey, indicating relatively minimal or insignificant contributions in this field.

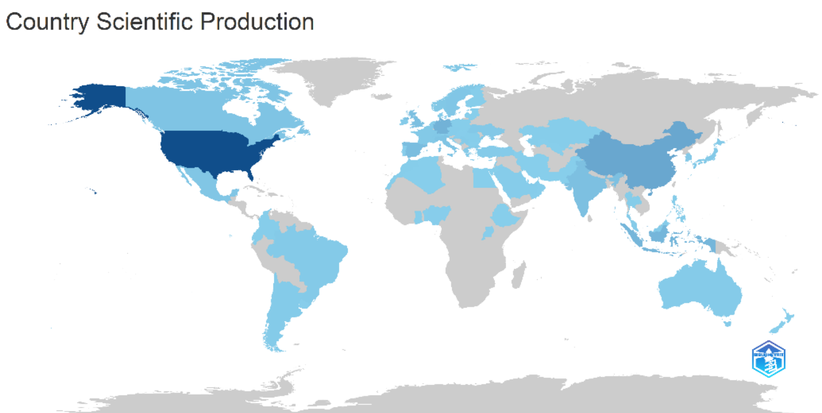

Figure 11. Countries' scientific production

Figure 12 shows the highest number of citations by country in research on the themes of Artificial Intelligence, Physics Education, and Education for Sustainable Development in the period 2015–2025. China ranks first with 2,313 citations, followed closely by the United States (USA) with 2,218 citations. Canada ranks third with 938 citations, while Germany (433 citations) and Singapore (367 citations) rank in the middle. Other countries with moderate citation counts include Belgium (270), Norway (233), the United Kingdom (183), and India (163). Indonesia also appears on the list, although its citation contribution is still relatively low (58 citations).

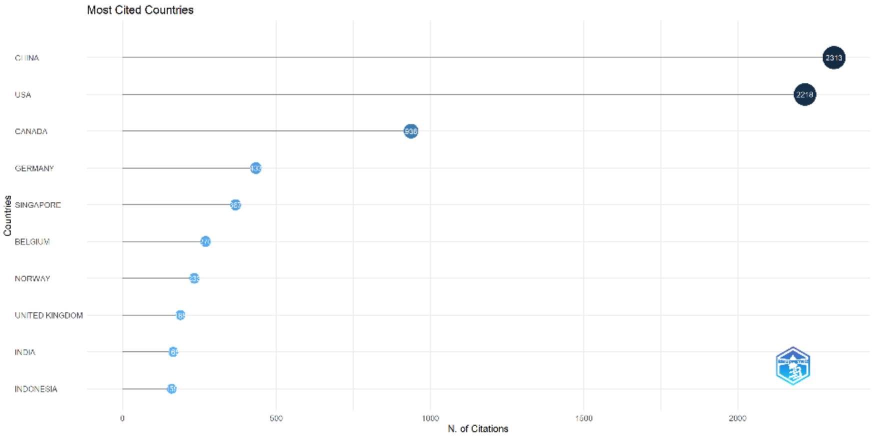

Figure 12. Most cited countries

Figure 13 shows the ten publications with the highest global citation impact in the period 2015–2025 in the fields of Artificial Intelligence, Physics Education, and Education for Sustainable Development. The article by Lu (2021, SIAM Review) ranks first with more than 1,400 citations, making it the most influential publication among all the documents analyzed. The second position is held by Wu (2017, Journal of Manufacturing Science and Engineering) with approximately 566 citations, followed by Xie (2020, Earthquake Spectra) with 377 citations. The article by Bhayana (2023, Radiology) also shows a high contribution, with 283 citations. Other notable publications are Janssens (2018, IEEE/ASME Transactions on Mechatronics) and Cai (2017, Interactive Learning Environments), with approximately 198 and 185 citations, respectively. Meanwhile, several other publications, such as Sun (2017), Mozaffar (2018), Vadyala (2022), and Panerati (2021), have lower citation counts, ranging from 40 to 80 citations.

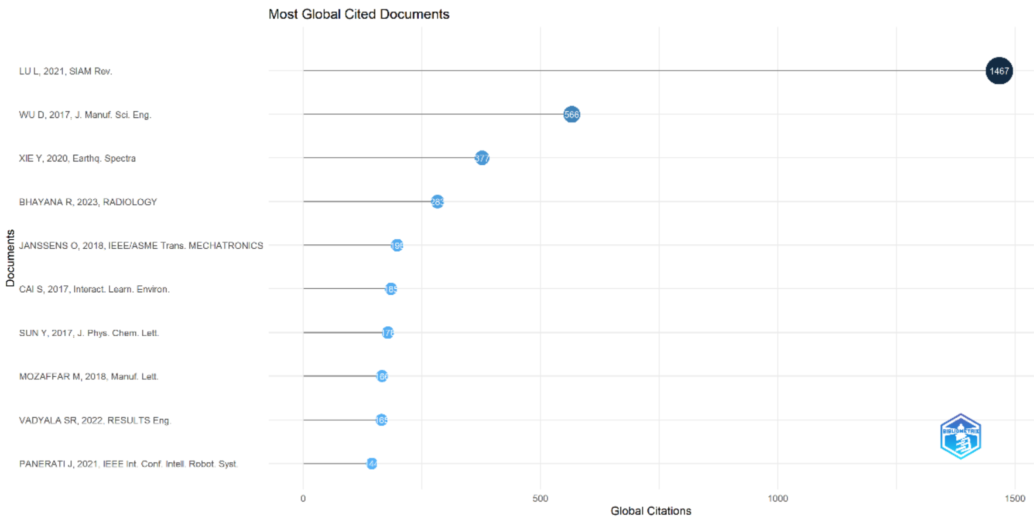

Figure 13. Most globally cited documents

Figure 14 shows the words that appear most frequently in publications related to Artificial Intelligence, Physics Education, and Education for Sustainable Development from 2015 to 2025. The largest words indicate the highest frequency, including "artificial intelligence," "engineering education," "students," and "education."
Additionally, words such as "machine learning," "deep learning," "learning systems," and "teaching" are prominent, underscoring AI's role in supporting the learning process. Other keywords, such as "physics education," "curricula," "active learning," "e-learning,"

and "neural networks," demonstrate the research's relevance to modern pedagogical practices and curriculum development. New words such as "ChatGPT," "forecasting," and "medical education" appear in smaller font, indicating emerging themes.

Figure 14. Most frequent words

Figure 15 shows that publications on the themes of Artificial Intelligence, Physics Education, and Education for Sustainable Development are dominated by the terms "engineering education", 'students', and "artificial intelligence". These three terms appear as the largest nodes and serve as the centre of connectivity among research topics. Several thematic groups are also visible: the red cluster emphasizes pedagogical aspects with words such as students, teaching, curricula, physics education, and active learning; the purple cluster represents the field of technology with terms such as machine learning, deep learning, learning systems, and neural networks; the green cluster is more related to the context of humans and education, featuring words such as curriculum, medical education, chatGPT, and learning; while the blue cluster connects research to broader fields such as STEM education, science education, augmented reality, and engineering and mathematics.

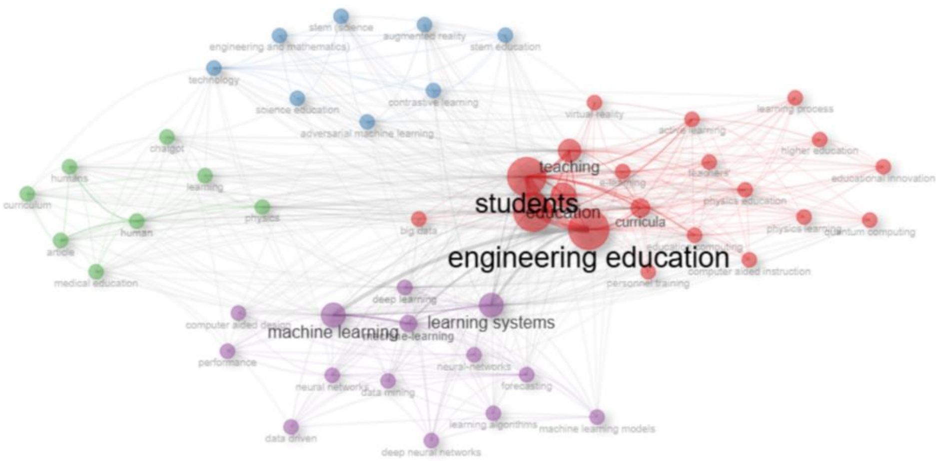

Figure 15. Co-occurrence network

Figure 16 shows the collaborative structure among authors in publications on Artificial Intelligence, Physics Education, and Education for Sustainable Development for the period 2015–2025. The largest network centres on Wulff P, Borowski A, and Mientus L, who form a strong collaborative core with Kubsch M. Their nodes are shown in large size, indicating consistent publication contributions and extensive connections with other researchers. Apart from this core group, there are several smaller collaboration clusters.

For example, the group consisting of Liu Y, Wang Y, Liu D, and Hu X forms a solid network in Asia; the group consisting of Zhang Y, Yan J, Sirnookar A, and Laverty JT collaborates on different themes; and there is also the collaboration between Lin Y, Cai J, and Wang Z. There are also pairs of authors such as Wibowo FC, Suprapto N, Gregorcic P, Polverini G, Rodrigo MMT, Shute VJ, and Nzabahimana J, Gumisirizah N, who tend to form bilateral relationships.

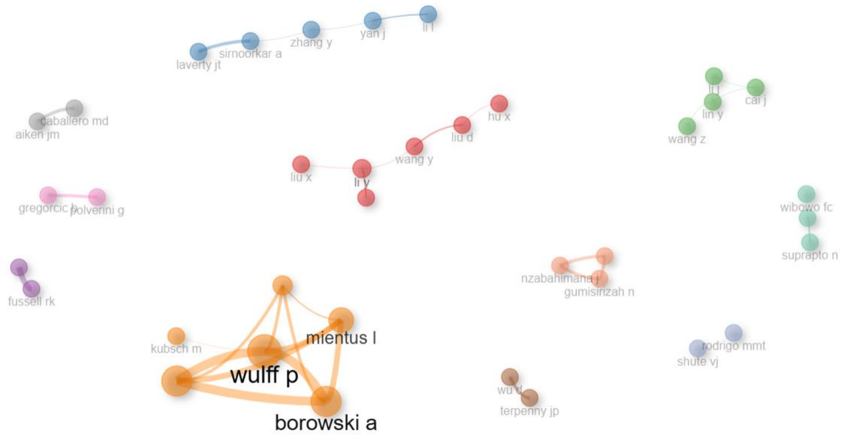

Figure 16. Co-occurrence network

Discussion

Annual scientific production

These results show that research on AI, physics education, and ESD has advanced significantly over the last decade. The surge in publications after 2019 aligns with the development of machine learning and deep learning technologies, which are increasingly used in higher education research (Zawacki-Richter et al., 2019). The sharp increase in 2022–2024 can be attributed to the emergence of large language models (LLMs) such as GPT-3 and GPT-4, which open up new opportunities for automated assessment, learning analytics, and generative simulations in physics classrooms (Kortemeyer, 2023; Wan & Chen, 2024). These findings are also consistent with bibliometric studies showing that AI research in education is a global trend across disciplines (Aria & Cuccurullo, 2017; Donthu et al., 2021). The decline in 2025 can be interpreted as a temporary phenomenon due to incomplete data collection (cut-off data) or an indication of a research consolidation phase after the publication boom in 2024. This trend also aligns with the literature that emphasizes the importance of consolidating AI research to advance the sustainable development agenda, given that the integration of advanced technology is not always linearly linked to improvements in learning quality (Vinuesa et al., 2020; Goralski & Tan, 2023). In general, this pattern confirms that this field of study is growing rapidly in quantity and moving towards a maturation phase characterized by diversification of themes, strengthened collaboration, and closer links with the SDGs in the context of physics education and ESD (Brundiers et al., 2021).

Sources' local impact

These results show that research on AI, physics, and ESD is published through various channels, ranging from specialized physics education journals to interdisciplinary journals and conference proceedings. The dominance of PRPER underscores the importance of specialised physics education publication channels as the primary venue for recent research contributions on AI for assessment, learning analytics, and simulation

(Kortemeyer, 2023; Wan & Chen, 2024). The presence of journals such as Computers and Education: Artificial Intelligence and Journal of Science Education and Technology also reflects the interdisciplinary nature of this field, where research is relevant not only to physics but also to educational technology in general (Donthu et al., 2021).

The inclusion of proceedings such as ASEE Conference Proceedings and CEUR Workshop Proceedings indicates that research in this field is still widely discussed in conference forums, which serve as incubators for new ideas before they develop into reputable journal publications. However, the lower H-index of proceedings compared to core journals indicates that greater citation impact tends to emerge from journal channels with a more stable community coverage (Zawacki-Richter et al., 2019).

This finding aligns with the global trend that research on AI in education is increasingly diversifying publications, strengthening core channels such as PRPER while expanding its reach to interdisciplinary forums relevant to sustainable education transformation (Brundiers et al., 2021; Goralski & Tan, 2023). Thus, this publication pattern reflects the field's maturing phase, in which the quality and impact of research are measured not only by the number of publications but also by contributions to scientific forums with broad reach and interdisciplinary relevance.

Sources' production over time

Figure 4 results confirm that AI research publications in physics education and ESD are not only centred in core journals but also appear in conference proceedings. The dominance of the Journal of Physics: Conference Series indicates that conferences remain the primary channel for disseminating the latest research, mainly exploratory or new methodological research, before it is developed into journal articles (Donthu et al., 2021). On the other hand, the growth of publications in PRPER confirms an important shift towards high-reputation peer-reviewed journals, which are increasingly becoming the primary reference for evidence-based research in physics education (Kortemeyer, 2023; Wan & Chen, 2024). The increased contribution of Physics Education highlights the role of pedagogical journals in connecting AI innovations with classroom practice, particularly for topics such as formative assessment, adaptive learning, and sustainability literacy (Brundiers et al., 2021). Meanwhile, the involvement of proceedings such as ASEE and SPIE underscores the interdisciplinary nature of this field, where AI innovations in physics education often emerge from engineering and technical forums (Zawacki-Richter et al., 2019; Goralski & Tan, 2023).

Most relevant authors

The distribution of author productivity shows that research contributions on AI integration in physics education and ESD are scattered, though several key figures are more productive. The presence of authors such as Li Y and Wulff P, the most significant contributors, indicates that specific research centres or groups have been actively promoting publications over the last decade. This is consistent with recent bibliometric findings that the field of physics education with AI support tends to be dominated by research groups that collaborate effectively and have access to the latest technologies, including machine learning and large language models (Donthu et al., 2021; Kortemeyer, 2023). Furthermore, the inclusion of names such as Caballero MD and Holmes NG underscores the importance of competency-based research and pedagogical innovation, where AI is positioned as a tool to enhance scientific literacy and support sustainability competencies (Brundiers et al., 2021). The presence of authors from interdisciplinary backgrounds, such as Dominguez A and Fussell RK, also indicates that this topic crosses traditional physics boundaries, leading to collaboration with computer science, engineering, and educational technology (Zawacki-Richter et al., 2019).

Authors' production over time

This productivity trend confirms that research at the intersection of AI, physics, and ESD is entering a growth phase, supported by consistent contributions from multiple authors. The ongoing contributions of Li Y, Wulff P, and Borowski A demonstrate the existence of strong research centres capable of maintaining continuous publication. This aligns with recent literature emphasising the importance of core authors' consistent productivity in driving new field development through international publication networks (Donthu et al., 2021). Furthermore, the emergence of authors such as Holmes NG and Caballero MD underscores the role of researchers in physics pedagogy in integrating AI to improve conceptual assessment and sustainability competencies (Brundiers et al., 2021; Kortemeyer, 2023). Interdisciplinary collaboration is also evident, with names such as Dominguez A and Chen Z coming from educational technology and computational science backgrounds, supporting previous findings that AI-education research develops most rapidly through cross-field collaboration (Zawacki-Richter et al., 2019; Goralski & Tan, 2023).

The 2023 productivity peak reflects the global momentum following the arrival of large language models such as GPT-3.5 and GPT-4, which triggered a surge in research on automated assessment and AI-based feedback (Wan & Chen, 2024). Going forward, this trend is expected to continue as research agendas increasingly focus on the ethics, sustainability, and practical impact of AI in the physics education ecosystem.

Authors' local impact

These findings indicate that scientific influence in AI research for physics education and ESD is not only determined by the number of publications, but also by the quality of citations generated. Wulff P's dominant position reflects his consistent contributions and frequent citations by other researchers, demonstrating a strong influence on shaping the current direction of research (Donthu et al., 2021). Meanwhile, authors such as Caballero, MD, and Holmes, NG, are known in the physics education literature as figures who emphasize the importance of conceptual assessment and data-driven pedagogical approaches (Kortemeyer, 2023). Their contributions in connecting AI with physics learning practices reinforce the impact of citations, even though their number of publications is not as high as that of the most prolific authors.

The inclusion of names such as Shute VJ and Chen Z signals an expansion of impact into the fields of educational technology and AI-based assessment. This is consistent with interdisciplinary trends that increasingly emphasize integrating AI to support sustainability competencies in higher education (Brundiers et al., 2021; Goralski & Tan, 2023).

Most relevant affiliations

The strategic implications: This distribution shows that AI research in physics education and ESD is a global agenda that involves cross-continental collaboration. Purdue University stands out as a major research centre in the United States. At the same time, Jakarta State University underscores the important role of institutions from the Global South, particularly Southeast Asia, in advancing contributions in this field. UNJ's involvement shows that the integration of AI and ESD in physics education is not limited to developed countries but is also a significant concern in developing countries, in line with international efforts to democratize educational technology (Brundiers et al., 2021; Goralski & Tan, 2023). European institutions such as KIT, Universität Potsdam, Universidad de Zaragoza, and Universitetet i Oslo demonstrate Europe's strategic position in interdisciplinary research linking AI with sustainability, according to a recent report on the roadmap for AI in higher education (Zawacki-Richter et al., 2019). Meanwhile, the involvement of major research universities such as Columbia University and Michigan State University underscores the support of institutions with high research capacity in science and technology education.

The relatively balanced involvement of universities in America, Europe, and Asia reinforces global bibliometric findings that AI-education research is increasingly collaborative and geographically dispersed (Donthu et al., 2021). This indicates that future research will increasingly emphasize cross-national collaboration to address ethical, pedagogical, and sustainability challenges in the use of AI in physics education.

Corresponding author's countries

The dominance of the United States reflects its large research capacity, supported by infrastructure, funding, and a strong tradition in STEM education. This aligns with the literature, which shows that the US remains the main centre of AI research and global science education (Donthu et al., 2021). However, China's strong position signals a significant shift in the research landscape, with the country increasingly becoming a major player in academic publications, including in AI and education (Zawacki-Richter et al., 2019). Interestingly, Indonesia has emerged as an important contributor, ranking third. This indicates an increase in research capacity in the Global South and the relevance of the AI–ESD agenda to developing countries. The involvement of UNJ and other universities in Indonesia in international publications reinforces the finding that developing countries are increasingly active in shaping the global discourse on technology-based sustainable education (Brundiers et al., 2021; Goralski & Tan, 2023).

The involvement of European countries (such as Germany, Spain, and the United Kingdom) and cross-country collaboration (MCP) confirms that this field is interdisciplinary and global. Such collaboration is essential to bring together expertise across disciplines, as integrating AI into physics education and ESD requires a combination of technological, pedagogical, and policy perspectives (Wan & Chen, 2024). Thus, this pattern shows that AI research in science education is becoming more inclusive, although it remains dominated by countries with large research capacities.

Countries' scientific production

This global distribution confirms that research on AI, physics education, and ESD is part of an international agenda, but contributions remain highly uneven. The dominance of the United States and China aligns with the literature, which shows that these two countries lead globally in AI research and science education, both in terms of publication quantity and international collaboration capacity (Zawacki-Richter et al., 2019; Donthu et al., 2021). Interestingly, Indonesia has emerged as one of the countries with relatively high productivity among developing countries. This shows an increase in academic capacity in the Global South, further strengthening the argument that the AI-based sustainable education agenda is not only dominated by developed countries but is also increasingly adopted in developing countries (Brundiers et al., 2021; Goralski & Tan, 2023).

The involvement of Western Europe (Germany, Spain, Italy, the United Kingdom) and Canada confirms that regions with strong research infrastructure play a significant role in expanding cross-country collaboration. However, the low contribution from Africa and parts of South Asia reflects a global gap in AI-education research. This aligns with recent findings that emphasise the need for global inclusivity in the development of educational technology to align with the Sustainable Development Goals (SDGs) agenda (Wan & Chen, 2024). Thus, this pattern shows that, even as AI-education research becomes increasingly global, collaborative efforts and international funding are still very much needed to strengthen participation by developing countries and narrow the global research gap.

Most cited countries

Thus, this pattern shows that, even as AI-education research becomes increasingly global, collaborative efforts and international funding are still very much needed to strengthen participation by developing countries and narrow the global research gap. This distribution shows that not all countries with a high number of publications have the same citation impact. China and the US, in addition to dominating in terms of publication quantity, also lead in quality, with much higher citation counts. This shows that research conducted in these two countries is often used as a global reference, cementing their position as centres of AI research and education (Donthu et al., 2021). Interestingly, Canada ranks third in citations, even though its publication output is not as large as that of China or the US. This suggests that Canadian research is more often cited for its quality or relevance, especially in the context of science and technology education (Zawacki-Richter et al., 2019). Singapore also stands out as a small Asian country with significant influence, demonstrating a strong national strategy in AI research and higher education (Goralski & Tan, 2023).

On the other hand, Indonesia, despite its increased publication productivity (see Figure 11 above), still has limited citation impact. This shows that, although developing countries are increasingly active in publishing, significant challenges remain in international recognition and citation penetration. This situation aligns with the literature emphasising the need for greater international collaboration, methodological rigour, and open access to publications to ensure research from the Global South is more recognisedwidely recognised (Brundiers et al., 2021; Wan & Chen, 2024). Thus, these data reveal a gap between publication productivity and citation impact, with developed countries continuing to lead in academic influence. In contrast, developing countries need to strengthen collaborative research strategies to make their contributions more visible on the global map.

Most globally cited documents.

These results show that the most cited documents do not always come directly from the physics education literature, but also from computing, engineering, and interdisciplinary applications. The article by Lu (2021) is particularly influential because it comprehensively discusses AI methods in SIAM Review, making it a key interdisciplinary reference (Donthu et al., 2021). Wu (2017) and Xie (2020) demonstrate the relevance of AI in manufacturing engineering and disaster mitigation, which, although not directly focused on physics education, still make important contributions to the development of technologies that are then adapted in the context of sustainable education (Goralski & Tan, 2023).

The article by Cai (2017) in Interactive Learning Environments emphasises the importance of AI research in the context of technology education, particularly for adaptive learning and data-based assessment, both of which are relevant to the ESD agenda (Zawacki-Richter et al., 2019). Meanwhile, recent publications such as Bhayana (2023) demonstrate the expansion of AI utilisation in health (radiology), which is also an example of interdisciplinary practice with broad application potential in STEM education (Wan & Chen, 2024). Thus, this citation pattern shows that the most influential literature in the field of AI-education is interdisciplinary: important contributions come from a combination of theoretical studies, technical applications, and pedagogical innovations. This confirms that AI research in physics education and ESD is grounded in a broad scientific basis, not limited to education, but also enriched by technology and applied science (Kortemeyer, 2023).

Most frequent words

This keyword pattern indicates that research in the field of AI and physics education focuses on two main streams: first, the use of AI technology (machine learning, deep learning, neural networks) to improve assessment, learning analytics, and educational personalization; second, the application of AI in a pedagogical context (students, curricula, teaching, active learning, physics education) oriented towards active learning and sustainability competencies (Brundiers et al., 2021). The dominance of the words "artificial intelligence" and "engineering education" indicates the interdisciplinary nature of this field, in which physics education is often integrated with engineering and digital technology. The presence of the word "ChatGPT" confirms the latest trend in the use of large language models (LLMs) for automated assessment and conceptual feedback, as explored in recent literature (Kortemeyer, 2023; Wan & Chen, 2024).

In addition, keywords such as "curricula" and "education computing" indicate a focus on integrating AI into curriculum design, which aligns with the Education for Sustainable Development agenda (Zawacki-Richter et al., 2019). These developments show that research is not only focused on technical applications, but also on the pedagogical, ethical, and social implications of AI use in education, in line with global discussions on sustainability and equitable access to technology (Goralski & Tan, 2023). Thus, this word cloud reflects the dynamics of research that balance technological innovation and educational transformation and increasingly emphasises the integration of AI in the context of sustainable physics learning.

Co-occurrence network

This pattern of interconnectivity shows that AI research in physics education is at the intersection of technological development and pedagogical innovation. The pedagogical cluster emphasises how AI supports active learning, formative assessment, and curriculum development aligned with sustainability competencies, in line with the Education for Sustainable Development (ESD) framework (Brundiers et al., 2021). On the other hand, the technology cluster highlights the key role of machine learning and deep learning as the foundation of innovation, which is now directly focused on students' learning experience, particularly in physics education (Kortemeyer, 2023; Wan & Chen, 2024). The presence of clusters containing words such as ChatGPT and medical education indicates that research topics are beginning to expand into interdisciplinary areas, linking

AI with health education and the use of large language models (LLMs) for automated assessment and conceptual feedback. Meanwhile, the blue cluster linking AI with STEM and augmented reality shows a new trend that encourages the integration of AI in cross-science and technology learning (Zawacki-Richter et al., 2019; Goralski & Tan, 2023). Thus, this keyword map confirms that AI–physics–ESD research is developing in an interdisciplinary manner, bringing together pedagogical innovation, digital technology, and the global sustainability agenda.

Collaboration network

This network structure shows that research collaboration in AI and physics education tends to be fragmented, with a single powerful core group (Europe/West) and several relatively separate smaller groups. The group Wulff P, Borowski A, and Mientus L stands out not only for its productivity but also for its frequent collaboration, making it a centre of citation and reference in the literature on technology-based physics education (Donthu et al., 2021). Meanwhile, collaborations from Asia, such as Liu Y and Wang Y, demonstrate the important role of Chinese researchers in expanding global contributions, in line with the trend of increasing Chinese publications in AI-education research (Zawacki-Richter et al., 2019). Collaborations from Indonesia, represented by Wibowo FC and Suprapto N, mark the role of developing countries in international research networks, albeit on a limited scale. This aligns with recent findings emphasising the importance of expanding international collaboration to ensure that research from the Global South gains wider recognition (Brundiers et al., 2021; Goralski & Tan, 2023).

The dominance of the European core group demonstrates the consistency of long-term research. At the same time, the emergence of new nodes, such as ChatGPT-related authors, signals a shift in research focus toward the use of large language models in physics education (Kortemeyer, 2023; Wan & Chen, 2024). Overall, this map confirms that although a global collaboration network has begun to form, there are still challenges in integrating clusters, especially between researchers in the West, Asia, and the Global South.

CONCLUSION

Fundamental Finding: Bibliometric analysis shows significant growth in AI research in physics education related to ESD over the past decade, with acceleration since 2019 driven by machine learning, deep learning, and Large Language Models (LLMs). **Implication:** The results confirm the dominance of the United States and China in publication output, with notable contributions from Indonesia as a representative of the Global South. The focus on reputable physics education journals underscores this field's strategic position in integrating AI, pedagogy, and global sustainability. **Limitation:** This study used only the Scopus database and did not evaluate the methodological quality or the practical effectiveness of AI in physics classrooms. **Future Research:** Further research is recommended to explore generative AI, federated learning, and physics-informed models, while encouraging dataset standardisation, ethically inclusive assessment, and strengthening cross-country collaboration to support the achievement of sustainable development goals through physics education.

AUTHOR CONTRIBUTIONS

Hanan Zaki Alhusni led the research and manuscript writing. **Riski Ramadani** processed and analysed bibliometric data. **Titin Sunarti** performed data validation and discussion. **Madlazim** strengthened the methodological aspects and relevance to the SDGs. **Muhammad Rey Dafa Ahmadi** supported the literature search, reference compilation, and final editing. All authors approved the final manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest, either financial or personal, that could influence the content or results of this study.

ETHICAL COMPLIANCE STATEMENT

This article has met the standards of research and publication ethics. The author affirms that this research is original, conducted with academic integrity, and free from unethical practices, including plagiarism.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The final responsibility for the content of the manuscript rests entirely with the authors. The author declares that this manuscript was prepared entirely without the assistance of artificial intelligence (AI) or other digital tools. The entire process, from planning, data processing, analysis, to writing and editing the manuscript, was carried out manually by the author. Thus, full responsibility for the content and authenticity of this article rests solely with the author.

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