Journal on Math and Science Educational Technology
Vol. 1, No. 2, December 2025
e-ISSN XXXX-XXXX
http://dx.doi.org/10.309xx/jmset.v1i2.78

ORIGINAL PAPER

Mapping Two Decades of Artificial Intelligence Research in Science Education: A Bibliometric Perspective (2000–2024)

Swasti Maharani (*), Hendrisa Rizqie Romandoni
Universitas PGRI Madiun

Accepted: December 20, 2025

Abstract
This study aims to map the global trend of publications related to artificial intelligence (AI) in science learning through bibliometric analysis. The primary concern is the limited understanding of the development of AI research themes in education, particularly in developing countries. The research method employs bibliometric analysis, utilizing data from the Scopus database, and is analyzed using VOSviewer software. A total of 118 relevant articles from 2000 to 2024 were analyzed based on publication patterns, collaborations between researchers, and geographical distribution. The study's results show a significant increase in the number of publications since the mid-2010s, with a peak in 2022. The most dominant topics include adaptive learning, learning analytics, and virtual simulation. Visualization of the collaborative network reveals high fragmentation, although several key authors and institutions are leading the research. The study also found that most publications originated from developed countries, with limited representation from developing countries. The study's conclusion confirms that AI has great potential for educational transformation; however, its implementation is still limited by technology and resource gaps. The limitations of this study include a lack of data from developing countries and a lack of exploration of the pedagogical impact of AI. Therefore, it is recommended that international collaborations be expanded and research focus on local contexts. Furthermore, an in-depth examination of the ethical and sustainability aspects of AI applications in education is necessary.

Keywords:
Artificial Intelligence
Science Education
Learning Technology

Corresponding Author:
Swasti Maharani
Email: swasti.mathedu@unipma.ac.id

INTRODUCTION

Artificial intelligence (AI) has great potential to support innovation in science learning in the digital era. AI technology enables the learning process to be more effective, adaptive, and personalized, which is relevant to the 4th Sustainable Development Goal (SDG), which is to ensure inclusive and quality education and support lifelong learning (Aswirna et al., 2022). In science education, AI can be utilized to create interactive simulations, analyze experimental data, and tailor learning materials to meet the diverse needs of students. This technology contributes to improved student engagement and learning outcomes through a more targeted data-driven approach (Luckin, 2019). Other studies confirm that AI can narrow the education gap by providing wider access to students, especially in areas with limited resources (Zawacki-Richter et al., 2019). Through the right approach, AI can be a crucial tool in achieving quality and sustainable education on a global level.

The application of AI in education has a significant impact on the development of interactive and adaptive learning methods. Technologies such as chatbots, smart tutoring systems, and learning

Published online: December 27, 2025

analytics can facilitate a more personalized and efficient learning experience. In science learning, for example, AI allows students to conduct complex virtual experiments without the need for a physical laboratory (Luckin & Holmes, 2016). Additionally, AI-based data analysis can help teachers understand students' needs and learning styles, enabling them to design more effective learning strategies (Wilton, 2022). The study's results also indicate that AI enhances student learning motivation through more interactive learning media (Baillifard, 2024). This impact confirms that AI is not only a technological tool but also a catalyst for educational transformation in the digital era.

Various challenges persist in integrating AI into science learning, particularly in developing countries. Technology gaps, such as limited internet access, as well as a lack of modern educational infrastructure, are major obstacles (Yasmin B. Kafai et al., 2012; Zawacki-Richter et al., 2019). Teacher competence is also an obstacle, because not all educators have the skills to utilize AI in learning effectively (Holmes, 1994; Norbert M. Seel, 2012). In addition, previous research has shown that most studies still focus on developing technology without considering its pedagogical and sustainability aspects (Aveleyra, 2023). This study aims to address these limitations by addressing questions such as: to what extent can AI enhance the quality of science learning, and how can its application be tailored to local needs? Bibliometric analysis in this study is expected to provide comprehensive, data-driven answers.

Research on the application of AI in science learning has shown significant development in the last two decades (Zawacki-Richter et al., 2019), noted that the number of publications discussing AI for education continues to increase, with a focus on the development of adaptive learning systems. Other research by (Baggio, 2020) shows that AI has great potential in supporting student data analysis and data-driven decision-making. Nonetheless, most of this research is conducted in developed countries with better access to technology. The literature examining the application of AI in developing countries, particularly in the context of science education, remains limited. Therefore, this study aims to complement the literature by providing more comprehensive insights through a bibliometric analysis approach.

The benefits of this research include significant theoretical and practical contributions. Theoretically, this study offers insight into AI research trends in science learning, including the identification of the most frequently discussed topics and patterns of collaboration among researchers. Practically, the results of this study can be a guide for educators, researchers, and policymakers to optimize the use of AI in science learning (Alizadeh, 2020). In addition, this research is expected to help identify research gaps and needs in AI development for a more inclusive educational context (Doroudi, 2023). Thus, the results of this study are not only beneficial for academics but also for practitioners and policymakers.

The results of previous studies showed a significant increase in the number of studies on the application of AI in science learning. Research by (Goel, 2017) revealed that topics such as adaptive learning and student data analytics dominate in the literature. Another study shows a trend in the use of AI in science experiment simulations that provide practical experience without the need for a physical laboratory (Hamal, 2022). In addition, collaborations between researchers and institutions in this field are also increasing, reflecting the growing global interest in the potential of AI in education. Nonetheless, the study also found significant gaps in the representation of local contexts, especially in developing countries.

Various aspects of AI research in science learning have not been fully explored. Previous research has tended to focus on the development of technology without evaluating its effectiveness in improving student learning outcomes (Luckin, 2019). Furthermore, studies examining the application of AI in local contexts, particularly in developing countries, remain limited. Analysis of local needs, as well as adaptation of technology to meet specific challenges such as limited infrastructure and teacher training, is often overlooked (Usak, 2024). This shortcoming underscores the need for more comprehensive research to bridge the gap between technological development and its practical applications.

This research makes an important contribution through a bibliometric analysis approach to understand global trends in AI research in science learning. This study provides a comprehensive overview of research patterns and emerging topics, identifying areas that have not been optimally explored. The bibliometric approach also enables in-depth analysis of inter-researcher collaboration, geographical representation, and publication distribution in the relevant literature. In addition, this research aims to fill the existing literature gap by providing empirical data that can inform the design of AI development strategies more relevant to global and local educational needs (Koedinger, 2016; Wen, 2024). The results of the research are expected to provide a new direction in the application of AI that is inclusive and effective in the context of science learning.

METHOD

This study employs a bibliometric analysis design, a statistical method used to examine scientific publications and map the academic landscape within a specific field of study. This approach involves analyzing the quantity and quality of publications, their origins, key actors, and the relationships between researchers. This analysis is qualitative descriptive, which involves identifying relevant data sources, collecting data, grouping based on specific categories, and providing an in-depth explanation of the patterns, conceptual frameworks, research methods, and main findings in the researched publications (Kuzior & Sira, 2022). Through this approach, the research will provide a comprehensive overview of the development of research in the field of AI in science learning from 2000 to 2024.

The primary source of data used in this study is Scopus. This comprehensive database encompasses multiple disciplines, offering access to the most recent scientific articles and publications in the fields of education and technology. The data search was conducted using keywords relevant to the research theme, specifically AI in science learning. The data search process consists of several stages, starting with the identification of articles based on appropriate titles and keywords. Furthermore, at the screening stage, irrelevant articles, such as non-journal or non-book documents, will be removed to ensure the quality of the data collected. At the feasibility stage, the abstract and title of the article are manually assessed to ensure they are relevant to the research topic. Articles that meet the inclusion criteria are articles published in English, available in journal or book form, and relevant to the topic of AI in science learning. Articles that are duplicates, irrelevant, or do not cover the application of AI in science learning will be excluded from this analysis. After screening, the relevant data will proceed to the bibliometric analysis stage. The following is the flow of data collection, as presented in Figure 1.

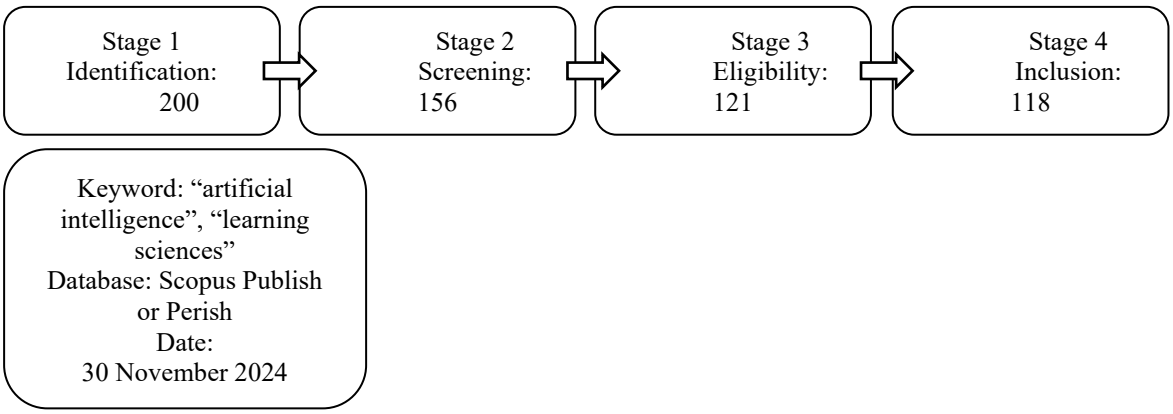

Figure 1. *Stages of Data Collection*

The data analysis technique employed in this study involves a bibliometric approach, which includes network visualization using VOSviewer to map the relationships between the authors, institutions, and countries involved in this study. This visualization helps to understand the collaboration and relationships between researchers in this field. Additionally, keyword analysis is conducted to identify the primary focus of the research by examining keywords that frequently appear in the collected publications. This aims to provide an overview of developing research topics. Furthermore, the distribution of publications by country, institution, and annual trends will be analyzed using Microsoft Excel, which allows the identification of the most productive regions or institutions in the study.

To assess the impact of a publication, the h-index and g-index will be calculated using Harzing's Publish or Perish. These two indices provide an overview of how often authors' work is cited by other researchers in the field, which can be used to assess the contribution and influence of each publication in the scientific literature related to AI in science learning. In addition, descriptive analysis was conducted to identify research patterns, conceptual frameworks, and key themes emerging from the articles taken for this analysis, which aimed to provide more in-depth insights into the direction of research and trends in the development of AI in science learning.

The data withdrawal procedure for this study was carried out on November 30, 2022, with a total of 118 articles reviewed that met the inclusion criteria. These articles have gone through several stages of screening and eligibility checks to ensure the relevance and quality of the data collected. This process aims to ensure that only publications genuinely related to AI topics in science learning are considered. The number of articles remaining after this screening stage is used to ensure the objectivity of the interpretation results. With the number of publications that have been filtered, this study provides a representative picture of research trends related to the application of AI in science learning throughout the research period

RESULTS & DISCUSSION

Global Research Trends

Figure 2 of the graph shows the global trend of artificial intelligence (AI) research publications and citations in science education from 2000 to 2024. This data consists of two main indicators: the number of publications per year (denoted by the blue line) and the number of citations per year (denoted by the orange line). Some key patterns can be identified, namely, the number of publications was relatively low until 2015, with an average of only 1–2 publications per year. Following 2016, there was a significant increase, particularly in 2022 and 2023, with the number of publications reaching a peak of 19 in 2023. The quotes show quite sharp fluctuations. The period from 2001 to 2008 saw several spikes in citations, despite the number of publications remaining low during that time. Citations reached their highest peak in 2022, with a figure of 246, indicating a significant influence from publications in the previous period. During this period, there has been a consistent increase in the number of publications and citations. However, 2024 showed a slight decrease in the number of citations compared to previous years, although the number of publications remained relatively stable.

From the data, it can be concluded that AI research in science education began to show a significant influence since the mid-2010s. One of the primary factors driving this increase in publications and citations is the advancement of AI technologies, including machine learning and data analytics, which are being increasingly applied in education. Study by (Wang, 2025) It has been noted that AI technology is being utilized to develop adaptive learning systems that enhance personalization in education, thereby drawing the attention of an increasing number of researchers.

The surge in citations in the early 2000s, despite the limited number of publications, can be interpreted as indicating that some of the publications from that period were seminal works that became the basis for further research. This is consistent with the phenomenon of "long tail citation," where

relevant early work remains a major reference in a rapidly growing field. The period after 2016 showed a significant acceleration in both publications and citations. This can be attributed to the increasing global attention to technology-based learning, as explained by Holmes et al. (2021), which shows that the integration of AI technology in learning can help develop critical thinking and problem-solving skills in students. This trend is also supported by the wider adoption of AI in higher education, as outlined by (Chen et al., 2022), which noted that global universities are beginning to integrate AI into curricula to support learning innovation.

Figure 2. *Global Research Trends*

The increase in 2022 and 2023 is likely to be influenced by the COVID-19 pandemic, which drove the massive digitalization of education. Study by (Bond et al., 2021) shows that AI-based distance learning has become one of the primary solutions during the pandemic, thereby attracting more researchers' attention to explore the potential of this technology in education. However, a decline in citations in 2024, despite the number of publications remaining stable, can be interpreted as a shift in research focus from basic exploration to practical application. The challenge of maintaining the quality and relevance of research is a major concern, as suggested by the (Niels Pinkwart & Sannyuya Liu, 2020), which emphasizes the importance of cross-disciplinary collaboration to promote the sustainability of research in this field.

Most Influential Of The Year

The H-Index and G-Index are two metrics commonly used to assess the impact and quality of scientific publications. The H-Index measures the productivity and citation rate of a researcher or research group by considering the number of publications that have at least an H-citation. Meanwhile, the G-Index is an alternative metric that gives more weight to publications with a high number of citations, thus reflecting the collective impact of those publications. Analyzing these two indices provides an overview of the development, relevance, and influence of research in a field of science, as well as helping to identify the main trends and focus of research in a given period. The following is presented in Figure 1 of the Most Influential of the Year chart.

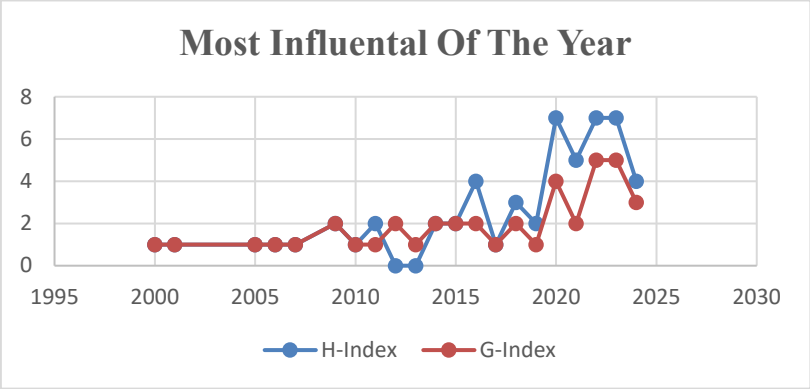

Figure 3. *Most Influential Of The Year*

The "Most Influential of the Year" graph illustrates the evolution of the H-Index and G-Index for research related to artificial intelligence (AI) in science learning from 2000 to 2024. In the first decade (2000-2010), both the H-Index and the G-Index showed stagnant values, namely at 1. Furthermore, the 2011-2015 period saw a slight increase in the G-Index, although it remained volatile, while the H-Index remained relatively low. The period from 2016 to 2020 marks a significant milestone in this study, during which both the H-Index and G-Index have experienced substantial increases. The peak of influence occurred in 2019, with the G-Index reaching a high of 7 and the H-Index reaching 5. However, during the 2021-2024 period, the G-Index exhibited a slight decline following its peak in 2019. In contrast, the H-Index continues to increase, reaching a high value of 4 in 2024.

Based on the analysis of data on the development of the H-Index and G-Index in artificial intelligence (AI) research in science education from 2000 to 2024, a significant pattern emerges in the evolution of research impact in this field. The early period exhibited limitations in the number and quality of publications, whereas the last decade witnessed a significant increase in influence. This trend offers valuable insights into how AI technology is becoming an increasingly integral part of science education innovation. Between 2000 and 2010, both the H-Index and the G-Index remained stagnant at a value of 1. This can be interpreted as a period of introduction of AI technology in the context of science education, where available publications have not received much attention from the scientific community. Penelitian sebelumnya oleh (Luckin, 2019) stated that the application of AI in education initially focused more on the development of intelligent tutoring systems (ITS) that aimed to provide a personalized learning experience. However, challenges such as limited technological infrastructure and a lack of adoption at the educational institution level have hindered rapid development in this period.

The subsequent period, from 2011 to 2020, exhibited a significant spike, particularly after 2016, when both the H-Index and G-Index increased sharply. 2019 was the peak of growth, with the G-Index reaching 7. This suggests that some publications are gaining widespread recognition, as evidenced by their high citation rates. This trend is in line with the growing global attention to technology-based learning, as revealed in the study (Scherer et al., 2019), who stated that the implementation of AI in education is increasingly attracting attention because of its potential in improving critical thinking skills, problem-solving, and personalization of learning.

In addition, this development can also be attributed to advances in big data technology and machine learning, which allow for in-depth analysis of students' learning behavior. Research (Zawacki-Richter et al., 2019). In their bibliometric review, they also demonstrated that AI in education during this period began to impact areas such as learning analytics and the adaptation of content based on student needs, which significantly increased the influence of research in this area. Meanwhile, during the 2021-2024 period, the H-Index continued to increase, reaching a value of 4 in 2024, although the G-Index showed a slight decline after peaking in 2019. This can be interpreted as a shift in focus from the number of publications that receive high citations to the stability of research that truly affects people

deeply. This trend shows that research in this area has entered a phase of maturity, where quality and long-term impact take precedence over quantity. However, the decline in the G-Index can also signal saturation or increasingly fierce competition in AI research, as noted by Minn (2022). This suggests that research in the field of educational technology necessitates a more innovative, multidisciplinary approach to maintain its relevance and appeal within the global scientific community.

These findings are consistent with the trends expressed by (Molenaar, 2023), which notes that the adoption of AI in education takes time to achieve massive adoption and recognition among academics. In addition, these results also underscore the importance of international collaboration in AI research, which has been driven by various global initiatives, such as the Artificial Intelligence in Education (AIED) initiative. Going forward, the focus of research should be directed to the development of more inclusive and adaptive algorithms to meet the needs of diverse students, including those from disadvantaged backgrounds. In addition, further research is needed to explore how AI can be used to support competency-based learning approaches and integrate ethical and fairness elements in AI systems, as suggested by (Nazari, 2021).

Most Cited Publication

The following table lists the 15 publications with the highest number of citations over the last two decades. The high number of citations in these publications reflects the significant influence of the research on the development and direction of research in this field. This data also shows that these works have high relevance in supporting scientific discussions and making meaningful contributions to the academic literature in the field of Artificial Intelligence in science education.

Table 1. *Most Cited Publication*

Cites	Authors	Title	Year	Source	Type	Cites Per Year
160	R. Luckin (Luckin, 2019)	Designing educational technologies in the age of AI: A learning sciences-driven approach	2019	British Journal of Educational Technology	Article	32
118	N. Nazari (Nazari, 2021)	Application of Artificial Intelligence-powered digital writing assistant in higher education: randomized controlled trial	2021	Heliyon	Article	39.33
97	J. Michael (Michael, 2001)	In pursuit of meaningful learning	2001	American Journal of Physiology - Advances in Physiology Education	Conf. Paper	4.22
87	A. Asuncion (Asuncion, 2009)	Asynchronous distributed learning of topic models	2009	Advances in Neural Information Processing Systems 21 - Proceedings of the 2008 Conference	Conf. Paper	5.8
78	D.B. Chin (Chin, 2010)	Preparing students for future learning with Teachable Agents	2010	Educational Technology Research and Development	Article	5.57
77	B.M. McLaren (McLaren, 2011)	Polite web-based intelligent tutors: Can they improve learning in classrooms?	2011	Computers and Education	Article	5.92

Cites	Authors	Title	Year	Source	Type	Cites Per Year
60	I. Molenaar (Molenaar, 2023)	Measuring self-regulated learning and the role of AI: Five years of research using multimodal multichannel data	2023	Computers in Human Behavior	Article	60
59	N. Yannier (Yannier, 2020)	Active Learning is About More Than Hands-On: A Mixed-Reality AI System to Support STEM Education	2020	International Journal of Artificial Intelligence in Education	Article	14.75
56	S. Doroudi (Doroudi, 2000)	Where is the Reward?: A Review of Reinforcement Learning for Instructional Sequencing	2000	International Journal of Artificial Intelligence in Education	Article	2.33
54	S. Järvelä (Järvelä, 2023)	Human and artificial intelligence collaboration for socially shared regulation in learning	2023	British Journal of Educational Technology	Article	54
54	Sein Minn (Minn, 2022)	AI-assisted knowledge assessment techniques for adaptive learning environments	2022	Computers and Education: Artificial Intelligence	Article	27
44	A.K. Goel (Goel, 2017)	Using AI to teach AI: Lessons from an online AI class	2017	AI Magazine	Article	6.29
43	S.Z. Salas-Pilco (Salas-Pilco, 2020)	The impact of AI and robotics on physical, social-emotional, and intellectual learning outcomes: An integrated analytical framework	2020	British Journal of Educational Technology	Article	10.75
37	R. Castro (Castro, 2009)	Human active learning	2009	Advances in Neural Information Processing Systems 21 - Proceedings of the 2008 Conference	Conf. Paper	2.47
35	M. Van Mechelen (Mechelen, 2023)	Emerging Technologies in K-12 Education: A Future HCI Research Agenda	2023	ACM Transactions on Computer-Human Interaction	Article	35

Research on the integration of Artificial Intelligence (AI) in science education shows significant developments over the past few decades. Based on data analysis, the most cited works were published between 2001 and 2023. The most influential publications are the works of (Luckin, 2019) Titled Designing educational technologies in the age of AI, published in the British Journal of Educational Technology. This article received 160 citations, reflecting the high interest in the topic of AI-based educational technology design. This shows its continued relevance to the challenges of adaptive learning and personalization in the digital age.

Most of the work on this list is published in reputable journals such as Heliyon and the American Journal of Physiology - Advances in Physiology Education, which confirms the role of reputable journals as a key platform for disseminating high-impact research. The majority of publications are journal articles, although there are also some conference papers. This trend is in line with the findings

(Eck & Waltman, 2009), which shows that works published in high-reputation journals are more likely to get significant citations because they have a wide readership. From a thematic perspective, these studies focus on the design of AI-based educational technology, AI applications in science teaching and learning, and efforts to enhance meaningful learning. For example, the research of (Nazari, 2021; Nazario et al., 2021) which discusses the application of AI for project-based teaching, provides practical insights into how these technologies can be applied to support collaborative learning. This research is also in line with the findings (Zawacki-Richter et al., 2019), which indicates that AI-based adaptive learning is a key theme in technology-based education.

The high number of citations in these publications shows the recognition from the scientific community of their contributions. (Jiménez, 2021) For example, it addresses the urgent needs of 21st-century education by offering insights into how AI can support personalized learning. This study aligns with other studies, such as those by Aisyah et al. (2023) and Wilton (2022), which discuss the development of AI-based adaptive learning systems, highlighting their thematic relevance at the global level. Going forward, the results of this study provide a clear direction for the development of further studies, particularly in optimizing AI to support STEM learning and advancing technology-based education policies. The integration of AI is expected to not only help more adaptive learning but also promote more effective cross-disciplinary collaboration, aligned with the challenges of modern education. The use of AI for adaptive, collaborative, and project-based learning is predicted to remain a major focus in the future, ensuring that education continues to evolve as technology advances.

Analysis Co-Authorship

The visualization below illustrates a network of co-authorship in artificial intelligence (AI) research on science education, created using VOSviewer software. The dots in the graph represent the author's name, while the size of the circle indicates the author's contribution or productivity based on the number of publications. The position and distance between the circles indicate the level of collaboration; Closer authors have closer cooperative relationships, while more distant authors show weak or no relationships.

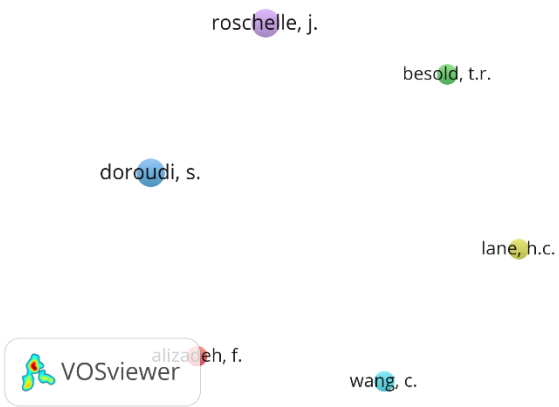

Figure 4. *Co-Authorship Visualization*

From this visualization, several major authors play a significant role in this field, including Roschelle, J., Doroudi, S., and Besold, T.R. Other notable authors, such as Lane, H.C., Wang, C., and Alizadeh, F., are also represented, albeit with relatively separate connections. There is no very large cluster, indicating that the collaboration network in this field is still fragmented, without a well-organized dominant group. Co-authorship is one of the key indicators in research that measures scientific collaboration. In this context, the visualization suggests that AI research in science education is still in

its early stages of development, characterized by a limited level of collaboration. Authors such as Roschelle, J., who has the largest circle, are likely major contributors to this field, both through their numerous publications and their influence on other research. Roschelle's previous research has shown the influence of AI technology on collaboration-based learning (Roschelle, 2021), so it is natural that he is one of the authors with high contributions.

However, the significant distance between authors reflects the fragmentation of the research network. This suggests that research in this field remains poorly organized, often focusing on regional or individual aspects rather than comprehensive studies. This fragmentation can also be attributed to the multidisciplinary nature of the field, where researchers come from diverse backgrounds, including computer science, education, and psychology. (Bond et al., 2021) emphasizing the importance of cross-disciplinary collaboration to produce high-impact research in technology-based education. Authors such as Doroudi, S., and Besold, T.R. may have been involved in seminal publications, but their connections with other authors appear to be isolated. This suggests that their findings may focus on specific themes that have not yet been integrated into the broader research community. For example, Doroudi, in his research, explores AI-based adaptive learning models, which significantly affect the personalization of education (Bellas et al., 2022)

Previous studies have highlighted the importance of collaborative networks in increasing scientific productivity and producing more comprehensive research. For example, a study by (Martin, 2006) shows that scientific collaboration not only improves the quantity of publications but also their quality through a multidisciplinary perspective. In the context of AI and science education, integrating knowledge from different disciplines is essential for developing innovative new approaches. This visualization is also relevant to the findings, which note that the field of educational technology often faces challenges in building a connected global research community, especially due to differences in language, culture, and research focus. In this regard, building an international network of collaborations can be a strategic step to strengthen the impact of AI research in science education.

Popular Keyword Analysis

The visualization below depicts a map of popular keywords in artificial intelligence (AI)-related research on science education, generated using VOSviewer software. The size of a keyword reflects the frequency with which it appears in a publication. In contrast, the position and distance between keywords indicate the relationship and co-existence rate across different articles. The keywords "technology", "system", and "assessment" appear to be the most dominant, indicating the themes that are most often discussed in the study. Other words, such as "teaching", "human interaction", and "facial expression recognition", add to the focus dimension of these studies.

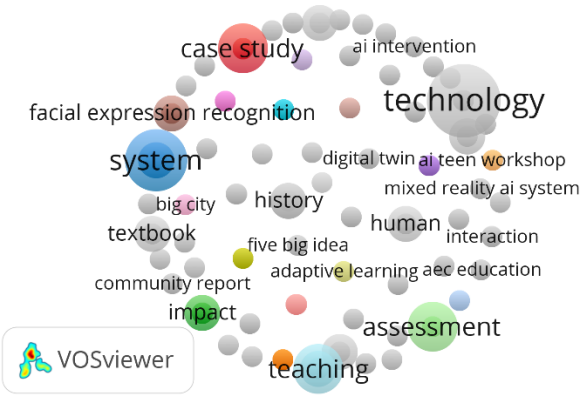

Figure 5. *Popular Keyword Analysis*

This keyword visualization reflects the research's focus on three main areas: technology development, learning support systems, and assessment in AI-based education. The most prominent keyword "technology" indicates that AI research in science education is driven by technological innovation, in line with previous research that underscores the role of technology in supporting science-based learning (Knight, 2018). The keyword "assessment" suggests that there is significant attention to evaluating the effectiveness of AI in education, both in measuring student learning outcomes and in understanding the impact of AI on pedagogy. For example, AI-based assessments are often used to provide adaptive feedback to students, as discussed by (Cho, 2020). This research emphasizes that AI technology not only improves the efficiency of the learning process but can also be used for personalization of learning, making it more relevant to individual needs.

Keywords such as "human interaction" and "facial expression recognition" indicate the focus of research on integrating AI to understand the affective and social aspects of learning. This is relevant to findings that emphasize the importance of students' emotional involvement in improving learning outcomes (D'Mello et al., 2014). Technologies such as facial expression recognition can help teachers or automated systems assess student engagement in real-time, a trend that is gaining momentum in AI-based education research. However, the presence of keywords such as "case study", "history", and "textbook" shows that this research also accommodates conventional and applied approaches. This indicates an effort to bridge new technologies with existing teaching methods, thereby expanding the acceptance of AI technology in the field of science education.

The focus on learning support technologies and systems shows parallels with research by (Luckin & Holmes, 2016) which emphasizes the importance of AI in improving educational accessibility and supporting adaptive learning. In addition, the dominance of these themes is also in line with the global trend that is driving the use of AI technology to support personalized learning (Hickmott et al., 2017). Furthermore, the keywords "adaptive learning" and "mixed reality" indicate the exploration of immersive technologies such as mixed reality in science education. This is relevant to studies that have found that immersive technology can improve students' understanding of abstract science concepts, for example, in virtual laboratory simulations (Eaton et al., 2022; Fowler et al., 2021). Based on the analysis of this keyword data, AI research in science education primarily focuses on the development of technology, learning systems, and assessment methods. This visualization highlights the significant impact of emerging technologies, including adaptive learning and mixed reality, on driving educational innovation. However, integration between technological approaches and traditional pedagogy remains essential to ensure wider acceptance. Increasing cross-disciplinary collaboration can also enrich research in this area, creating a more holistic and relevant approach to future education.

CONCLUSION

Research on artificial intelligence (AI) in science education has shown significant development over the last two decades, particularly since the mid-2010s. The number of publications and citations has increased sharply, reflecting the high interest and influence of this research in the global scientific community. The surge in publications since 2016 has been driven by technological advances, including machine learning and data analytics, while the peak in citations in 2022 highlights the relevance and significant impact of previous research. In terms of collaboration, the co-authorship network exhibits a high degree of fragmentation, although several major authors make significant contributions, such as Roschelle and Doroudi. The decline in citations in 2024 and the stability of publications indicate a shift in focus from initial exploration to practical application. This trend indicates that AI research in science education has entered a phase of maturity. However, this study has some limitations. The degree of fragmentation of the author's network indicates a lack of cross-disciplinary and geographic collaboration, which can limit the diversity of perspectives. The majority of research still focuses on the

context of developed countries, so the relevance of the results in developing countries is less explored. For further research, it is recommended to strengthen cross-disciplinary collaboration through a global platform that can expand the scope of the study and increase the universal relevance of the results. In addition, there needs to be a focus on the application of AI in the context of education in developing countries to ensure technological inclusivity. Studies on the ethical and security impacts of data also need to be expanded, especially in the management of student data, to ensure that the application of AI supports the principles of fair, safe, and sustainable learning.

REFERENCES

Aisyah, S., Najib, M., Rahmanita, B. N., & Prastowo, A. (2023). Drill and Practice Berbasis Video terhadap Efektivitas Belajar Matematika Siswa di Sekolah Dasar Negeri 15 Palembang. *AR-RIAYAH : Jurnal Pendidikan Dasar*, *7*(1), 45–60. https://doi.org/10.29240/jpd.v7i1.6063

Alizadeh, F. (2020). eXplainable AI: Take one Step Back, Move two Steps forward: Investigating Folk Theories and Users' Perception of Artificial Intelligence. *Lecture Notes in Informatics (LNI), Proceedings - Series of the Gesellschaft Fur Informatik (GI)*.

Asunción, A. (2009). Asynchronous distributed learning of topic models. *Advances in Neural Information Processing Systems 21 - Proceedings of the 2008 Conference*.

Aswirna, P., Kiswanda, V., Nurhasnah, N., & Fahmi, R. (2022). Implementation of STEM E-Module with SDGs Principles to Improve Science Literacy and Environment-friendly Attitudes in Terms of Gender. *JTK (Jurnal Tadris Kimiya)*, *7*(1), 64–77.

Aveleyra, E. E. (2023). Artificial intelligence in Physics teaching. *Proceedings of the LACCEI International Multi-Conference for Engineering, Education and Technology*, *2023*. https://api.elsevier.com/content/abstract/scopus_id/85172304596

Baggio, B. (2020). AI and education reborn. *ICSIT 2020 - 11th International Conference on Society and Information Technologies, Proceedings*.

Baillifard, A. (2024). Effective learning with a personal AI tutor: A case study. *Education and Information Technologies*, *Query date: November 30, 2024, 11:25:32*.

Bellas, F., Guerreiro-Santalla, S., Naya, M., & Duro, R. J. (2022). AI Curriculum for European High Schools: An Embedded Intelligence Approach. *International Journal of Artificial Intelligence in Education*, *33*(2), 399–426. https://doi.org/10.1007/s40593-022-00315-0

Bond, M., Bedenlier, S., Marín, V. I., & Händel, M. (2021). Emergency remote teaching in higher education: Mapping the first global online semester. *International Journal of Educational Technology in Higher Education*, *18*(1), 50. https://doi.org/10.1186/s41239-021-00282-x

Castro, R. (2009). Human active learning. *Advances in Neural Information Processing Systems 21 - Proceedings of the 2008 Conference*.

Chen, X., Zou, D., Xie, H., Cheng, G., & Liu, C. (2022). Two Decades of Artificial Intelligence in Education: Contributors, Collaborations, Research Topics, Challenges, and Future Directions. *Educational Technology & Society*, *25*(1), 28–47.

Chin, D. B. (2010). Preparing students for future learning with Teachable Agents. *Educational Technology Research and Development*, *58*(6), 649–669. https://doi.org/10.1007/s11423-010-9154-5

Cho, E. (2020). Trends of Educational Technology in Korea and the U.S.: A Report on the AECT-Korean Society for Educational Technology (KSET) Panel Discussion. *TechTrends*, *64*(3), 357–360. https://doi.org/10.1007/s11528-020-00493-5

D'Mello, S., Lehman, B., Pekrun, R., & Graesser, A. (2014). Confusion can be beneficial for learning. *Learning and Instruction*, *29*, 153–170. https://doi.org/10.1016/j.learninstruc.2012.05.003

Doroudi, S. (2000). Where is the Reward?: A Review of Reinforcement Learning for Instructional Sequencing. *International Journal of Artificial Intelligence in Education*, *29*(4), 568–620.

Doroudi, S. (2023). The Intertwined Histories of Artificial Intelligence and Education. *International Journal of Artificial Intelligence in Education*, *33*(4), 885–928. https://doi.org/10.1007/s40593-022-00313-2

Eaton, W. M., Burnham, M., Robertson, T., Arbuckle, J. G., Brasier, K. J., Burbach, M. E., Church, S. P., Hart-Fredeluces, G., Jackson-Smith, D., Wildermuth, G., Canfield, K. N., Córdova, S. C., Chatelain, C. D., Fowler, L. B., Hendawy, M. M. Z. elAbdeen, Kirchhoff, C. J., Manheim, M. K., Martinez, R. O., Mook, A., … Rogers, A. (2022). Advancing the scholarship and practice of stakeholder engagement in working landscapes: A co-produced research agenda. *Socio-Ecological Practice Research*, *4*(4), 283–304. https://doi.org/10.1007/s42532-022-00132-8

Eck, N. van, & Waltman, L. (2009). *Software survey: VOSviewer, a computer program for bibliometric mapping*. https://doi.org/10.1007/s11192-009-0146-3

Fowler, S., Cutting, C., Kennedy, J., Leonard, S. N., Gabriel, F., & Jaeschke, W. (2021). Technology-enhanced learning environments and the potential for enhancing spatial reasoning: A mixed-methods study. *Mathematics Education Research Journal*, *34*(4), 887–910. https://doi.org/10.1007/s13394-021-00368-9

Goel, A. K. (2017). Using AI to teach AI: Lessons from an online AI class. *AI Magazine*, *38*(2), 48–58. https://doi.org/10.1609/aimag.v38i2.2732

Hamal, O. (2022). Artificial Intelligence in Education. *Sustainability (Switzerland)*, *14*(5). https://doi.org/10.3390/su14052862

Hickmott, D., Prieto-Rodriguez, E., & Holmes, K. (2017). A Scoping Review of Studies on Computational Thinking in K–12 Mathematics Classrooms. *Digital Experiences in Mathematics Education*, *4*(1), 48–69. https://doi.org/10.1007/s40751-017-0038-8

Holmes, G. (1994). WEKA: A machine learning workbench. *Australian and New Zealand Conference on Intelligent Information Systems - Proceedings*.

Järvelä, S. (2023). Human and artificial intelligence collaboration for socially shared regulation in learning. *British Journal of Educational Technology*, *54*(5), 1057–1076. https://doi.org/10.1111/bjet.13325

Jiménez, Y. (2021). Artificial Intelligence in Neuroeducation: The Influence of Emotions in the Learning Science. *Advances in Intelligent Systems and Computing*, *1277*. https://doi.org/10.1007/978-3-030-60467-7_6

Knight, S. (2018). Augmenting formative writing assessment with learning analytics: A design abstraction approach. *Proceedings of International Conference of the Learning Sciences, ICLS*, *3*(2018), 1783–1790.

Koedinger, K. R. (2016). An Interview Reflection on "Intelligent Tutoring Goes to School in the Big City." *International Journal of Artificial Intelligence in Education*, *26*(1), 13–24. https://doi.org/10.1007/s40593-015-0082-8

Kuzior, A., & Sira, M. (2022). A Bibliometric Analysis of Blockchain Technology Research Using VOSviewer. *Sustainability*, *14*(13), Article 13. https://doi.org/10.3390/su14138206

Luckin, R. (2019). Designing educational technologies in the age of AI: A learning sciences-driven approach. *British Journal of Educational Technology*, *50*(6), 2824–2838. https://doi.org/10.1111/bjet.12861

Luckin, R., & Holmes, W. (2016). Intelligence Unleashed: An argument for AI in Education. In *UCL Knowledge Lab: London, UK.* [Report]. UCL Knowledge Lab. https://www.pearson.com/content/dam/corporate/global/pearson-dot-com/files/innovation/Intelligence-Unleashed-Publication.pdf

Martin, D. B. (2006). Mathematics Learning and Participation as Racialized Forms of Experience: African American Parents Speak on the Struggle for Mathematics Literacy. *Mathematical Thinking and Learning*, *8*(3), 197–229. https://doi.org/10.1207/s15327833mtl0803_2

McLaren, B. M. (2011). Polite web-based intelligent tutors: Can they improve learning in classrooms? *Computers & Education*, *56*(3), 574–584. https://doi.org/10.1016/j.compedu.2010.09.019

Mechelen, M. V. (2023). Emerging Technologies in K-12 Education: A Future HCI Research Agenda. *ACM Transactions on Computer-Human Interaction*, *30*(3). https://doi.org/10.1145/3569897

Michael, J. (2001). In pursuit of meaningful learning. *American Journal of Physiology - Advances in Physiology Education*, *25*(1), 145–158. https://doi.org/10.1152/advances.2001.25.3.145

Minn, S. (2022). AI-assisted knowledge assessment techniques for adaptive learning environments. *Computers and Education: Artificial Intelligence*, *3*. https://doi.org/10.1016/j.caeai.2022.100050

Molenaar, I. (2023). Measuring self-regulated learning and the role of AI: Five years of research using multimodal multichannel data. *Computers in Human Behavior*, *139*. https://doi.org/10.1016/j.chb.2022.107540

Nazari, N. (2021). Application of Artificial Intelligence powered digital writing assistant in higher education: Randomized controlled trial. *Heliyon*, *7*(5). https://doi.org/10.1016/j.heliyon.2021.e07014

Nazario, A. P., de Lima, V. F., Fonseca, L. M. M., Leite, A. M., & Scochi, C. G. S. (2021). Development and evaluation of an educational video for families on the relief of acute pain in babies. *Revista Gaúcha de Enfermagem*, *42*, e20190386. https://doi.org/10.1590/1983-1447.2021.20190386

Niels Pinkwart & Sannyuya Liu (Eds.). (2020). *Artificial Intelligence Supported Educational Technologies* (pub.1127241249). https://doi.org/10.1007/978-3-030-41099-5

Norbert M. Seel (Ed.). (2012). *Encyclopedia of the Sciences of Learning* (pub.1034155265). https://doi.org/10.1007/978-1-4419-1428-6

Roschelle, J. (2021). Intelligence Augmentation for Collaborative Learning. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *12792*(Query date: 2024-11-30 11:25:32), 254–264.

Salas-Pilco, S. Z. (2020). The impact of AI and robotics on physical, social-emotional, and intellectual learning outcomes: An integrated analytical framework. *British Journal of Educational Technology*, *51*(5), 1808–1825. https://doi.org/10.1111/bjet.12984

Scherer, R., Siddiq, F., & Tondeur, J. (2019). The technology acceptance model (TAM): A meta-analytic structural equation modeling approach to explaining teachers' adoption of digital technology in education. *Computers & Education*, *128*, 13–35.

Usak, M. (2024). Artificial Intelligence In Biology Education. *Journal of Baltic Science Education*, *23*(5), 806–808. https://doi.org/10.33225/jbse/24.23.806

Wang, C. (2025). Application of artificial intelligence for feature engineering in education sector and learning science. *Alexandria Engineering Journal*, *110*, 108–115.

Wen, Q. (2024). Analysis of the Current Research Status of Intelligent Education in China Based on Knowledge Graph. *Proceedings - 2024 6th International Conference on Computer Science and Technologies in Education, CSTE 2024*, 56–61.

Wilton, L. (2022). Where Is the AI? AI Literacy for Educators. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *13356*(Query date: 2024-11-30 11:25:32), 180–188.

Yannier, N. (2020). Active Learning is About More Than Hands-On: A Mixed-Reality AI System to Support STEM Education. *International Journal of Artificial Intelligence in Education*, *30*(1), 74–96. https://doi.org/10.1007/s40593-020-00194-3

Yasmin B. Kafai, William A. Sandoval, Noel Enyedy, Althea Scott Nixon, & Francisco Herrera (Eds.). (2012). *Embracing Diversity in the Learning Sciences* (pub.1021350905).

Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education – where are the educators? *International Journal of Educational Technology in Higher Education*, *16*(1), 39.