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# A Decade of Artificial Intelligence and Machine Learning in School Education: A Bibliometric Analysis (2015–2024)

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**Abstract.** In the past decade, the use of Artificial Intelligence (AI) and Machine Learning (ML) in school education has experienced rapid growth. This study aims to analyze trends in annual scientific publications, average citations, thematic evolution, keyword co-occurrence, and author collaboration (co-authorship) related to this topic. Data were retrieved from the Scopus database for the period 2015–2024 and analyzed using Biblioshiny and VOSviewer. The analysis reveals a significant surge in publications after 2020, with a high level of global collaboration and a dominance of contributions from developed countries such as the United States and Finland. Thematic evolution reveals a shift from technical topics such as machine learning and data science toward more applied and contextual issues, including AI literacy, ChatGPT, and secondary education. Keyword mapping identifies five key clusters, emphasizing AI integration in education systems, personalized learning technologies, and the intersection of AI with social and ethical concerns. This study offers a comprehensive overview of the scholarly landscape and highlights challenges such as unequal adoption in developing countries, algorithmic bias, and the need for inclusive, ethical education policies. The findings aim to guide researchers, educators, and policymakers in promoting AI-informed teacher training, developing relevant AI literacy curricula, and fostering international collaboration to support equitable and effective use of intelligent technologies in school education.

**Keywords:** artificial intelligence; bibliometric analysis; machine learning; school education

## INTRODUCTION

Over the past decade, the advancement of digital technology has brought significant transformation across various sectors, including education. Artificial Intelligence (AI) and Machine Learning (ML) have emerged as two technologies increasingly applied to enhance the effectiveness of teaching and learning processes in schools. There has been notable progress in developing AI/ML curricula in schools, accompanied by various learning tools and innovative pedagogical approaches, including project-based learning and human-computer collaboration. Implementing these technologies not only automates teachers' administrative tasks but also holds great potential in supporting personalized learning, data-driven assessment, and more accurate decision-making in education. AI and ML have been used to personalize instruction, optimize learning pathways, and improve student engagement and academic outcomes through adaptive systems and intelligent tutors (Martin et al., 2024; Yim & Su, 2024). These technologies help automate teachers' administrative work, conduct data-based evaluations, and provide more accurate feedback for educational decision-making (Gligorea et al., 2023; Suna & Özer, 2025; Zafari et al., 2022).

Despite the increasing use of AI and ML in school education, there are various challenges and disparities in adoption across countries. On the one hand, developed countries demonstrate broader adoption and contribute dominantly to scientific publications, whereas developing countries continue to face obstacles such as inadequate infrastructure, limited human resources, and a lack of supportive policies. Research and adoption of AI/ML in schools are predominantly carried out in developed nations, particularly the United States. In contrast, developing countries face barriers related to infrastructure, human resources, and policy (Sanusi et al., 2024). Other challenges include algorithmic bias, data privacy concerns, and the lack of attention to underrepresented groups (Mahon et al., 2023; Southgate, 2021). Therefore, it is essential to understand the global scientific landscape on this topic as a foundation for policy-making and further development. International collaboration and policies that support equitable adoption, teacher training, and relevant curriculum development are urgently needed (Grover et al., 2024).

Bibliometric research is a method used to analyze scientific trends and the knowledge structure within a field. This article examines how AI and ML have been applied in the context of

school education over the past decade. The study seeks to address this gap by using data from the Scopus database and analyzing it through VOSviewer and Biblioshiny tools.

This approach allows researchers to observe the dynamics of scientific publications, collaboration among authors and countries, and emerging core research themes. This study provides a global mapping of scientific contributions and highlights key actors and the evolution of relevant research topics. The novelty of this research lies in its specific thematic focus on school education and the ten-year period aligned with recent technological developments. Bibliometric studies in the field of education have leveraged tools such as VOSviewer and Biblioshiny for visualizing collaboration networks, keyword analysis, and mapping thematic evolution (Martin et al., 2024; Zafari et al., 2022).

More specifically, the aim of this article is to analyze annual scientific production, average citation count, thematic evolution, keyword co-occurrence, and author collaboration (co-authorship). Therefore, the findings of this study are expected to serve as a strategic reference for researchers, educators, and policymakers in understanding and advancing the optimal use of AI and ML in school education in the future.

## METHODS

This study employed a quantitative approach using bibliometric methods to analyze the scientific development related to using Artificial Intelligence (AI) and Machine Learning (ML) in school education over the past decade, specifically from 2015 to 2024. Data were collected from the Scopus database due to its extensive coverage and credibility in international scientific literature. The search strategy involved a combination of keywords applied to titles, abstracts, and author keywords: ("artificial intelligence" OR "AI") AND ("machine learning" OR "ML") AND ("school education" OR "primary education" OR "secondary education" OR "K-12" OR "elementary school" OR "high school"), with filters for document type as articles (doctype: ar) and publication years after 2014. The complete search query was as follows:

(TITLE-ABS-KEY("artificial intelligence" OR "AI") AND TITLE-ABS-KEY("machine learning" OR "ML") AND TITLE-ABS-KEY("school education" OR "primary education" OR "secondary education" OR "K-12" OR "elementary school" OR "high school") AND PUBYEAR > 2014 AND DOCTYPE(ar))

The retrieved data were then exported in BibTeX and CSV formats for analysis using two main software tools: Biblioshiny (the visual interface of Bibliometrix in RStudio) and VOSviewer. Biblioshiny was used to analyze annual scientific production, average citation counts, and topic trends. Meanwhile, VOSviewer was employed to visualize collaboration networks among authors (co-authorship) and keyword co-occurrence.

To ensure data validity, only documents that met the criteria of topical relevance and were classified as scientific journal articles were included in the analysis. Manual filtering was conducted to verify that selected articles specifically focused on school education, excluding higher education or other sectors. Furthermore, the software tools used in this study are well-established and widely utilized in international bibliometric research, ensuring accuracy in both data processing and visualization.

## RESULTS AND DISCUSSION

### Main Data Distribution

During the study period from 2016 to 2025, this topic demonstrated rapid growth, with a total of 152 articles published across 92 sources or scientific journals. The average annual growth rate of publications reached 43%, indicating a significant increase in interest in this area. The average age of documents was only 1.88 years, reinforcing the indication that this is a relatively new and continuously evolving topic. Each document received an average of 18.07 citations a relatively high figure that reflects considerable attention from the scientific community. In total, 8,293 references were cited across all publications.

In terms of keyword indexing, the system generated 936 terms via Keywords Plus (ID), while authors manually assigned 528 Author's Keywords (DE). Regarding authorship, there were 677 contributors, with only nine articles written by a single author, indicating a very high level of collaboration an average of 4.96 authors per document. Moreover, international collaboration reached 27.63%, demonstrating that this topic holds global relevance and has garnered international attention.

| Description | Results |
|---|---|
| MAIN INFORMATION ABOUT DATA | |
| Timespan | 2016:2025 |
| Sources (Journals, Books, etc) | 92 |
| Documents | 152 |
| Annual Growth Rate % | 43 |
| Document Average Age | 1.88 |
| Average citations per doc | 18.07 |
| References | 8293 |
| DOCUMENT CONTENTS | |
| Keywords Plus (ID) | 936 |
| Author's Keywords (DE) | 528 |
| AUTHORS | |
| Authors | 677 |
| Authors of single-authored docs | 9 |
| AUTHORS COLLABORATION | |
| Single-authored docs | 9 |
| Co-Authors per Doc | 4.96 |
| International co-authorships % | 27.63 |
| DOCUMENT TYPES | |
| article | 152 |

**Figure 1.** Data Distribution

With an annual growth rate of 43% (figure 1) and an average document age of only 1.88 years, it is evident that the topic of AI and ML in school education is currently in rapid development. This significant increase reflects a global need to revolutionize primary and secondary education systems in alignment with technological advancements. The high level of international collaboration (27.63%) further indicates that this issue has received broad attention across countries.

**Annual Scientific Production**

The annual publication growth reveals a significant increase in articles since 2021, peaking in 2024. This trend indicates that AI and ML technologies have begun to receive serious attention in school education practices, especially following the emergence of adaptive learning technologies and the COVID-19 pandemic, which accelerated the widespread digitalization of education.

An analysis of publication trends during the 2016–2025 (table 1) period shows a compelling dynamic in developing research on this topic. In the early phase, from 2016 to 2020, the number of publications remained very low and fluctuated, with an average of fewer than three articles per year. A significant surge occurred in 2021 when the number of publications increased nearly sixfold compared to the previous year. This upward trend continued, reaching its peak in 2024 with 57 publications, reflecting substantial post-pandemic interest in the topic. As of the data collection in 2025, 25 articles had already been published a relatively high number with the potential to increase further.

The sharp rise after 2020 was most likely driven by the push for online learning innovations during the pandemic, the expanding integration of technology into educational systems, and the growing demand for personalized learning powered by artificial intelligence (AI) and machine learning (ML), particularly at the primary and secondary education levels. Overall, this trend illustrates an exponential increase in academic interest regarding the application of AI and ML in school settings. Research in this area has grown dramatically, especially since 2015, with a surge in publications and global collaborations. The field is highly interdisciplinary and rapidly expanding across countries and levels of education (Abuhassna, 2024; Martin et al., 2024; Paek & Kim, 2021).

**Table 1.** Annual Scientific Production

| **Year** | 2025 | 2024 | 2023 | 2022 | 2021 | 2020 | 2019 | 2018 | 2017 | 2016 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Articles** | 25 | 57 | 23 | 22 | 17 | 3 | 3 | 1 | 0 | 1 |

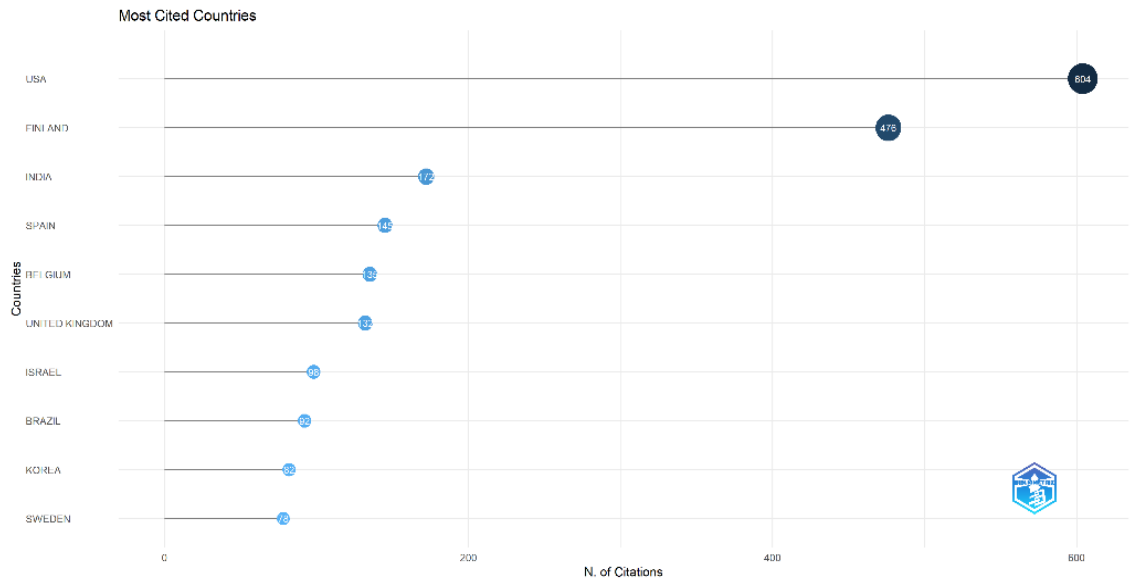


**Figure 2.** Citations

**Average Citations**

Other countries that ranked in the top ten include India (172 citations), Spain (145), Belgium (135), the United Kingdom (132), Israel (98), Brazil (92), South Korea (82), and Sweden (78). The high number of citations from these countries reflects scientific productivity and the high relevance and significant contribution to advancing knowledge in this field.

These findings (figure 2) indicate that although a country's number of documents may not be the highest, citation count can strongly indicate the quality and impact of the research produced. Notably, the dominance of the United States and Finland highlights these countries' critical role in the global landscape of technology-based education. Regarding citations, the United States also ranks with the highest number of citations, reflecting its strong scientific influence. Countries such as the United Kingdom and China also reported high average citation counts, underscoring the quality and relevance of research publications from these regions. Despite this rapid growth, ongoing challenges remain, particularly regarding equitable access, teacher training, curriculum alignment, and addressing ethical and social issues related to AI in education (Mahon et al., 2023; Zhai et al., 2021).

**Thematic Evolution**

Based on the results of the thematic evolution (figure 3) analysis of keywords from scientific publications on artificial intelligence (AI) in education, there is a noticeable shift in research focus from 2016 to 2025. During the 2016–2024 period, the dominant themes included machine learning, artificial intelligence (AI), data science applications in education, and education. These themes indicate that research throughout the decade primarily centered on the general application of AI technologies in educational contexts, with an emphasis on technical aspects and the potential integration of AI into teaching and learning practices.

However, by 2025, there will be a significant shift toward more contextual and specific topics such as AI education, AI literacy, ChatGPT, and secondary education, along with the continued prominence of machine learning. This change reflects growing attention toward learners' understanding of AI concepts, the importance of AI literacy, and the application of generative AI technologies like ChatGPT in formal educational settings. The transition pathways between themes reveal that earlier research has laid a strong foundation for the exploration of newer, more application-oriented, and user-centered topics.

The implications of these findings suggest that going forward, curriculum development, digital literacy, and institutional readiness—especially at the secondary and tertiary levels—will become strategic areas requiring serious attention. Moreover, future research is advised to place greater emphasis on pedagogical, ethical, and policy aspects of AI integration in education to effectively address the challenges posed by the

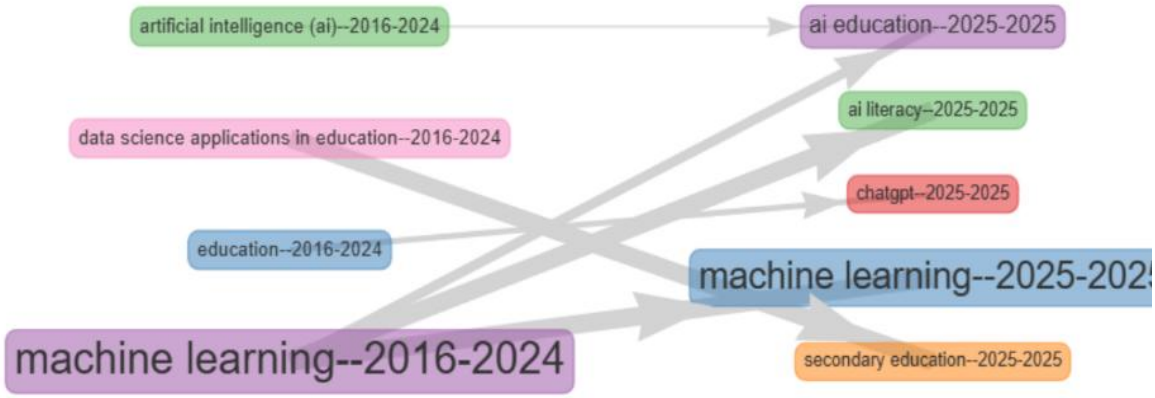


**Figure 3.** Thematic Evolution

industrial revolution and the rapid pace of technological advancement.

**Keyword co-occurrence**

The network analysis identified five major clusters ( figure 4) representing interconnected focus areas and demonstrating significant thematic development (with a minimum of five keyword co-occurrences for accuracy).

**Green Cluster: Integration of AI and ML in Educational Systems**

This cluster lies at the network's core, with dominant keywords such as artificial intelligence, machine learning, education, and K-12. It shows that most publications emphasize the application of artificial intelligence technologies in formal education, spanning from primary to higher education levels. The connection to keywords like AI education and AI literacy indicates a growing focus on digital literacy and institutional readiness to face the age of artificial intelligence.

**Yellow Cluster: Learning Technologies and Students**

This cluster places students at the center of the discourse, closely linked to educational computing, learning systems, and data mining. The primary focus is leveraging machine learning-based technologies to support personalized learning, enhance learning outcomes, and implement adaptive learning algorithms. It reflects a pedagogical transformation that uses data and technology to support students' academic achievement.

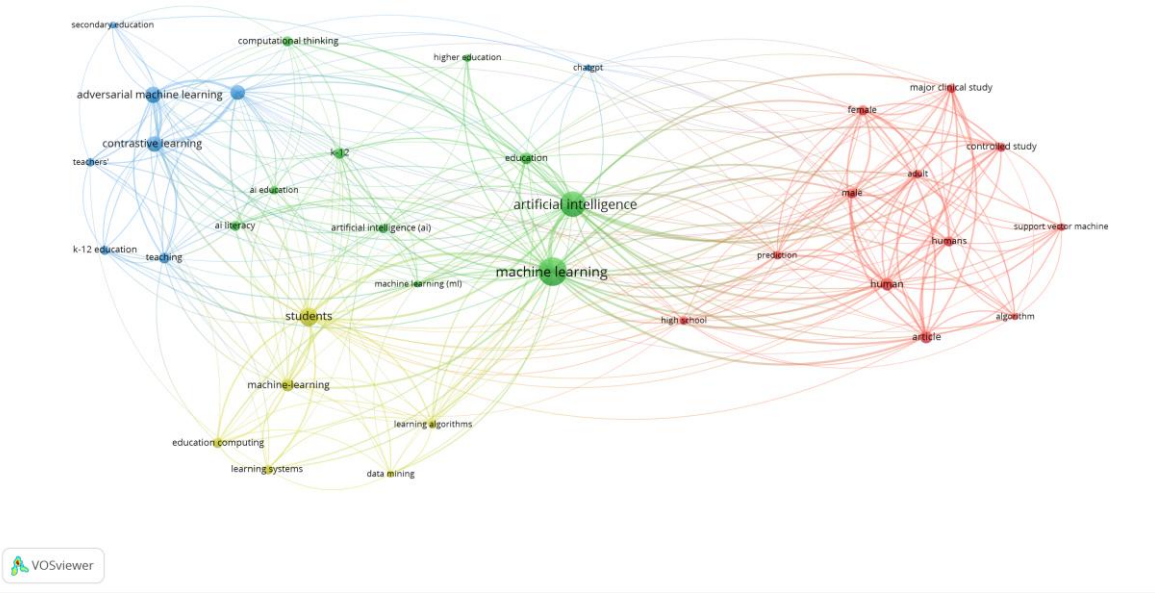


**Figure 4. Keyword** co-occurrence

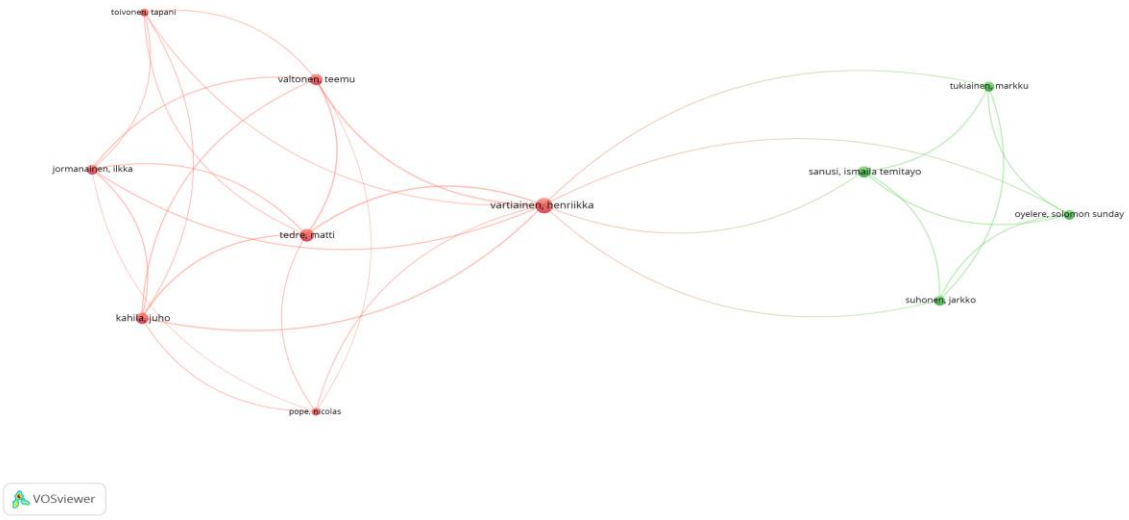


**Figure 5.** Author Collaboration

**Blue Cluster: Cutting-Edge AI Technologies in K-12 Education**

This cluster is characterized by contrastive, adversarial machine learning, secondary education, and teachers. It reflects recent trends in applying advanced machine learning techniques within the context of primary and secondary education. The appearance of keywords like ChatGPT also indicates the increasing adoption of large language models in classroom practices as teaching aids and interactive learning media for students. There is a growing emphasis on teaching AI literacy at the K-12 level using age-appropriate tools (e.g., Teachable Machine, Machine Learning for Kids, Scratch, Python) and employing project-based or game-based learning approaches (Paek & Kim, 2021; Yim & Su, 2024).

**Red Cluster: AI and ML Studies in Human Contexts**

Distinct from the other clusters, this group emphasizes the application of machine learning in human-centered studies, with keywords such as human, male, female, controlled study, and support vector machine. Although not directly focused on education, its connections imply intersections between AI-based medical/psychological research and educational development such as in student mental health or adaptive learning for special needs.

Overall, these findings suggest that research on AI and ML in school education has grown quantitatively and become more complex and multidisciplinary. Over the past decade, the research focus has shifted from technical exploration to practical applications that consider key actors such as students and teachers, cutting-edge technologies, and the integration of intelligent learning systems. Furthermore, the interconnections between clusters indicate that technological innovations in education are not isolated but are influenced by and contribute to developments in medical, social, and ethical domains. AI and ML are extensively used to create personalized and adaptive learning environments, optimize learning paths, increase engagement, and improve academic performance. Adaptive learning systems utilize machine learning to dynamically adjust content and strategies to meet the individual needs of students (Shaumiwaty et al., 2025).

**Author Collaboration**

Based on the analysis conducted (figure 5) using VOSviewer with a minimum threshold of two co-authorships, the visualization of the author collaboration network reveals two main clusters that reflect patterns of cooperation in scholarly publications on this topic.

The first cluster comprises seven authors: Ilkka Jormanainen, Juho Kahila, Nicolas Pope, Matti Tedre, Tapani Toivonen, Teemu Valtonen, and Henriikka Vartiainen. This group exhibits a strong interconnectedness, characterized by intensive collaboration among the authors. Henriikka Vartiainen holds a central position within this cluster, acting as the main connector and establishing links across clusters.

The second cluster comprises four authors: Solomon Sunday Oyelere, Ismaila Temitayo Sanusi, Jarkko Suhonen, and Markku Tukiainen, who also demonstrate a high level of collaborative

engagement. Interestingly, Henriikka Vartiainen bridges the two clusters, highlighting her pivotal role in fostering inter-group and potentially international collaborations.

This pattern underscores the high level of collaboration within the academic community in this field. It indicates a well-established network structure with strong potential for further expansion of collaborative research.

## CONCLUSION

This study reveals a significant rise in publications and citations on Artificial Intelligence (AI) and Machine Learning (ML) in school education from 2015 to 2024, with a notable surge after 2020 driven by accelerated digitalization during the COVID-19 pandemic. A bibliometric analysis of 152 articles from 92 journals shows strong author collaboration, a globally connected research network, and major contributions from developed countries like the United States and Finland. The research focus has shifted from technical aspects to pedagogical concerns, such as AI literacy, ChatGPT integration, and the readiness of schools to adopt generative technologies. Keyword analysis identifies five main clusters, including AI in education systems, personalized learning, and human-AI interactions. The study highlights key challenges unequal adoption, algorithmic bias, and the need for ethical, inclusive policies while calling on educators, researchers, and policymakers to promote AI-based teacher training, design relevant AI curricula, and foster global collaboration for equitable and effective use of AI in education.

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