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MAPPING RESEARCH ON DIGITAL COMPETENCIES IN SCIENCE EDUCATION: A BIBLIOMETRIC ANALYSIS

*Estéfano Vizconde Veraszto**
Universidade Federal de São Carlos, campus Araras, São Paulo, Brasil
https://orcid.org/0000-0002-4029-4803

*Antonio Medina Rivilla***
Universidad Nacional de Educación a Distancia, Madrid, España
https://orcid.org/0000-0002-1483-0668

*Eufrásio Peréz Navio****
Univesridad de Jaén, Jaén, España
https://orcid.org/0000-0001-8688-9602

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ABSTRACT

This study maps the development of digital competencies in science education through a bibliometric analysis from 2005 to 2024. Digital competencies are essential in disciplines such as biology, chemistry, and physics, yet challenges like limited infrastructure and inadequate teacher training hinder integration. Artificial Intelligence is a promising tool to support digital competency development by enabling adaptive and personalized learning. Using VOSviewer and SciMAT, 64 articles from Web of Science were analyzed, identifying 393 keywords. Results show the connection between AI and science education and emphasize the need for policies promoting continuous teacher training and effective Information and Communication Technologies use. The study concludes that AI can personalize learning, automate assessments, and create interactive

* Physicist and Ph.D. in Education, Science, and Technology from the Universidade Estadual de Campinas, with a research stay at the Universidad Complutense de Madrid. Associate Professor at the Universidade Federal de São Carlos, in the Department of Natural Sciences and Mathematics. Permanent faculty member of the Graduate Program in Science and Mathematics Education (UFSCar) and the Graduate Program in Education (UNICAMP). Coordinator of the Undergraduate Physics Program at UFSCar Araras. Email: estefanovv@ufscar.br.

** Teacher, Education Supervisor, Bachelor in Pedagogy and Psychology, and Ph.D. in Educational Sciences – Pedagogy from the Universidad Complutense de Madrid (UCM). Emeritus Professor at UNED and Honorary Doctor (Doctor Honoris Causa) from several universities: UniSantander (Mexico) and IUNIR (Argentina), Distinguished Doctor from Latvia, and Lifetime Achievement Award in Research from the Educational Research Association – Cuba-Mexico. Director of more than 170 doctoral dissertations and numerous master's theses, as well as doctoral programs in various countries and universities. Editor of numerous renowned academic works and coordinator of specialized education journals in several countries. Email: amedina@edu.uned.es.

*** Ph.D. in Philosophy and Educational Sciences from UNED-Spain, with various research and teaching stays at universities in Europe, Africa, and the Americas, the most recent at the Università degli Studi di Urbino Carlo Bo (Italy). Full Professor and member of the Governing Council at the Universidad de Jaén (UJA), and coordinator of the UJA's training program for early-career teachers. Email: epnavio@ujaen.es.

content, enhancing digital competencies in science education.
Keywords: Digital competencies; Artificial Intelligence; Science Education; Bibliometric Analysis; VOSviewer; SciMat.

RESUMEN

MAPEO DE INVESTIGACIONES SOBRE COMPETENCIAS DIGITALES EN LA EDUCACIÓN EN CIENCIAS: UN ANÁLISIS BIBLIOMÉTRICO

Este estudio mapea el desarrollo de competencias digitales en la educación científica mediante un análisis bibliométrico de 2005 a 2024. Estas competencias son esenciales en disciplinas como biología, química y física, pero desafíos como infraestructura limitada y formación docente inadecuada dificultan su integración. La Inteligencia Artificial emerge como herramienta prometedora para favorecer un aprendizaje adaptativo y personalizado. Usando VOSviewer y SciMAT, se analizaron 64 artículos de Web of Science, identificando 393 palabras clave. Los resultados muestran la conexión entre IA y educación científica, y subrayan la necesidad de políticas que impulsen la formación continua del profesorado y el uso eficaz de la Tecnologías de Información e Comunicación. Se concluye que la IA puede personalizar el aprendizaje, automatizar evaluaciones y crear contenidos interactivos, fortaleciendo las competencias digitales en la enseñanza de las ciencias.
Palabras clave: Competencias digitales; Inteligencia Artificial; Educación en Ciencias; Análisis Bibliométrico; VOSviewer; SciMat.

RESUMO

MAPEANDO PESQUISAS SOBRE COMPETÊNCIAS DIGITAIS NA EDUCAÇÃO EM CIÊNCIAS: UMA ANÁLISE BIBLIOMÉTRICA

Este estudo mapeia o desenvolvimento de competências digitais na educação em ciências através de análise bibliométrica de 2005 a 2024. As competências digitais são essenciais em disciplinas como biologia, química e física, mas desafios como infraestrutura limitada e formação inadequada de professores dificultam sua integração. A Inteligência Artificial surge como ferramenta promissora para apoiar o desenvolvimento dessas competências, possibilitando aprendizagem adaptativa e personalizada. Utilizando o VOSviewer e o SciMAT, foram analisados 64 artigos da Web of Science, identificando 393 palavras-chave. Os resultados mostram a conexão entre IA e educação em ciências e enfatizam a necessidade de políticas que promovam a formação contínua de professores e o uso eficaz das Tecnologias da Informação e Comunicação. O estudo conclui que a IA pode personalizar a aprendizagem, automatizar avaliações e criar conteúdos interativos, aprimorando as competências digitais na educação em ciências.
Palavras-chave: Competências digitais; Inteligência Artificial; Educação em Ciências; Análise Bibliométrica; VOSviewer; SciMat.

Introduction[1]

Digital competencies are essential for the conscious and safe use of digital technologies in educational, social, and professional contexts. These competencies encompass skills such as finding, evaluating, using, sharing, and creating digital content, promoting digital inclusion, facilitating education, improving communication and collaboration, and ensuring online security (Marin et al., 2022; Kwiatkowska & Wiśniewska-Nogaj, 2022). In education, they prepare students for the challenges of a digitalized society (Barahona, 2023). In sciences, disciplines such as biology, chemistry, physics, and geology require computational technologies, simulations, and data analysis, as well as skills like critical thinking, problem-solving, and collaboration (Hussain & Bhatti, 2022). The development of these competencies makes the learning process more dynamic and interactive, facilitating the exploration of complex concepts and promoting investigative skills (Barahona, 2023). It also empowers students to access and evaluate online educational resources, including scientific databases and virtual simulations (Tapalova et al., 2022). However, inadequate teacher training compromises the full integration of ICT in science education (Domene et al., 2023).

Science education faces challenges such as the availability of technological infrastructure in schools, teacher training, and ensuring the security and privacy of student data (Barahona, 2023). The lack of institutional support and limited time for continuous teacher development are significant obstacles (López Melero & Pérez Navío, 2023). In this context, Artificial Intelligence (AI) emerges as a tool to enhance students' digital competencies, creating adaptive and personalized learning environments. However, the implementation of this technology requires a careful and ethical approach, ensuring transparency, accountability, and the protection of student data privacy (Hussain & Bhatti, 2022). Given the importance of digital competencies in science education, this research proposes a bibliometric investigation using VOSviewer and SciMAT to examine trends, patterns, and gaps in the development of these competencies between 2005 and 2024 (Barahona, 2023). The bibliometric analysis aims to identify the development stage and key scientific contributions, understanding the challenges in implementing these educational practices, particularly in technological infrastructure, teacher training, and data security. AI is seen as a promising ally to improve learning, requiring an ethical and careful approach (Tapalova et al., 2022). A comprehensive search in the Web of Science mapped works on this theme, seeking to contribute to discussions on science education and teacher training.

Thus, this work seeks to answer the following question: What are the trends, patterns, and gaps in the development of digital competencies in science education over the past two decades as reflected in the scientific literature?

Therefore, the research aims to conduct a bibliometric analysis of the state of the art in research on the development of digital competencies in science education, covering the period from 2005 to 2024, using VOSviewer and SciMAT for analysis. To achieve this purpose, the following specific objectives will be explored:

a. Map the scientific production related to digital competencies in science education, identifying areas of interest.
b. Investigate the temporal evolution of publications.
c. Explore the geographical distribution, identifying the impact of scientific production.
d. Identify possibilities and challenges in the research area to guide future studies on the topic.

The research is justified by the importance of understanding the current state of studies

1 Texto revisado, normalizado e traduzido por Mariane da Silva Domingos Del Duca.

on digital competencies in science education, considering that the results can address emerging needs in this field and guide future investigations (Domene et al., 2023; Medina et al., 2023).

Theoretical Foundation

Digital competencies aid in the effective use of digital technologies in educational, social, and professional contexts. In the educational environment, these competencies help prepare students for the challenges of a digitalized society (Barahona, 2023). In science education, disciplines such as biology, chemistry, and physics often require computational technologies, simulations, and data analysis (Hussain & Bhatti, 2022). Besides technical mastery, digital competencies encompass transversal skills such as critical thinking, problem-solving, and collaboration.

The development of digital competencies in science education facilitates the exploration of complex concepts, promoting investigative skills (Barahona, 2023). This allows students to access various online educational resources, such as scientific databases and virtual simulations, enhancing their knowledge and practical skills (Tapalova et al., 2022; Anaya Garay et al., 2022). However, the adoption of these strategies faces significant challenges, including the availability of technological infrastructure and continuous teacher training (López Melero & Pérez Navío, 2023). Ensuring the security and privacy of student data is also a growing concern, requiring robust approaches to protect the integrity of personal information (Barahona, 2023).

In this context, Artificial Intelligence (AI) emerges as a promising tool to enhance students' digital competencies, promoting personalized learning and creating adaptive learning environments tailored to individual student needs (Hussain & Bhatti, 2022). However, the implementation of AI in science education must be approached with caution, ensuring transparency, accountability, and the protection of student data privacy and security to avoid algorithmic biases and discrimination. Thus, despite the growing relevance of digital competencies, it is essential to understand the challenges in effectively implementing these educational practices, particularly regarding technological infrastructure, teacher training, and data security and privacy issues (Tapalova et al., 2022).

Continuous teacher training in digital competencies can improve teaching and learning processes, promoting a culture of professional development (Ruiz-Cabezas et al., 2020). Institutional support and ongoing training are also necessary for the effective implementation of ICT in the educational environment (López Melero & Pérez Navío, 2023). The importance of continuous teacher training for improving the quality of education is a crucial point that needs consideration (Medina et al., 2023).

Methodology

This research is based on bibliometric analysis assumptions, offering a comprehensive perspective of scientific production in a specific area, highlighting patterns, trends, emerging themes, and priority areas of interest (Bagheri et al., 2023; Pritchard, 1969). It is an investigative tool that allows the assessment of the impact and visibility of publications, the measurement of collaboration between researchers and institutions, and the identification of knowledge gaps that can guide future investigations (Van Raan, 2009).

Using bibliometric indicators and data visualization software, such as SciMAT (Science Mapping Analysis Tool) and VOSviewer employed in this study, it is possible to analyze and graphically represent the relationships between concepts, regions, and authors (Leydesdorff & Rafols, 2008). SciMAT was chosen because it offers citation analysis and impact indices, enabling the identification of interaction patterns between different research areas and the visualization of the structure and evolution of scientific fields through keyword co-occurrence analysis (Cobo et al., 2012). In addition, it generates strategic diagrams based on centrality and density measures, allowing for the identification of consolidated, emerging, or declining themes over time.

VOSviewer was chosen because it enables the analysis and visualization of thematic categories and the dynamic exploration of the structure of scientific literature (Van Eck & Waltman, 2009). The software stands out for generating interactive bibliometric maps based on co-occurrence of keywords, co-citation, co-authorship, and bibliographic coupling networks, providing an intuitive and visually rich interface to identify clusters and trends in research fields.

Bibliometric Research

Searches on the Web of Science were conducted using specific terms. The first search, using the terms "AI" ("Artificial Intelligence"), "Digital Competence", "Development", "Science Education", "Natural Sciences", "Educational Technology", and "Education," resulted in only 3 articles. The second search, focusing on "Digital Competence," "Development," and "Science Education," identified 64 articles. The term "Education" was added in the third search, and again, 64 articles were found, indicating that this term did not expand the scope of the research, suggesting that it may not be essential for the research objectives.

Considering the search conducted and the research objectives, it is worth noting that the term "Digital Competence" was used to direct the research towards studies on the development and promotion of digital competencies in the educational context, covering aspects such as digital literacy, digital security, and online communication. The term "Development" was included to explore how digital competencies are acquired, enhanced, and integrated over time in the educational environment, including teaching strategies, educational policies, and teacher training programs. The term "Science Education" restricted the research to the specific context of science education, focusing on disciplines such as biology, chemistry, and physics, investigating the use of digital technologies, including AI.

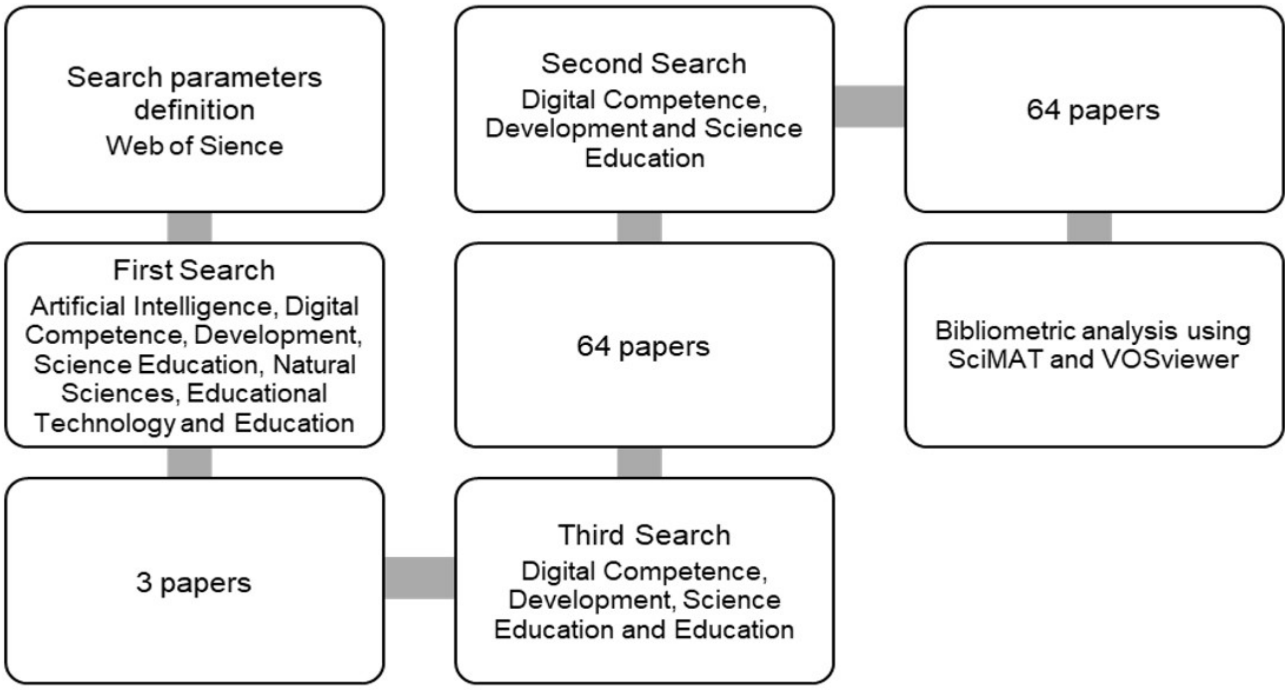
The inclusion of the term "Education" aimed to ensure that the results encompassed general studies on education, educational policies, and pedagogical practices, and their connection with digital competence and the use of technology in science education. However, this was not realized as already pointed out.

Thus, the combination of these terms sought a comprehensive and in-depth perspective on the investigated theme. Finally, it is worth noting that no restrictions were imposed on the searches regarding knowledge areas, document types, or periods. Since the result was 64 articles, it was considered that the number is not too large and new restrictions could limit the research. Even so, the diversity of the articles provides a representative basis to analyze trends, challenges, and opportunities in using AI to promote digital competencies in science education.

Data Analysis

Initially, the analysis was conducted by period, comprising the groupings of 2005-2009, 2010-2014, 2015-2019, and 2020-2024. Although there were 4 articles for the first two periods highlighted (Table 1), the analysis could not categorize them. Discarding two periods was not considered the most appropriate strategy if the intention is to analyze the state of the art within the same theme. Therefore, the final option was to redo the analysis globally, considering the total production (64 articles) from 2005 to 2024. The flowchart of the bibliometric research process is represented in Figure 1.

Figure 1: Bibliometric research process.



Source: The authors.

Table 1: Articles analyzed, by period.

Period	Documents	%
2005-2009	1	1,6%
2010-2014	3	4,7%
2015-2019	15	23,4%
2019-2024	45	70,3%
2005-2024	64	100%

Source: The authors.

The data imported into the software, VOSviewer, allowed for the identification of the countries that produce and publish the most in the area (Table 2). The analysis of countries reveals different levels of involvement and impact in research on digital competencies in science education. China, with 11 documents and 123 citations, stands out for its volume and significant impact on the scientific literature, although it shows relatively low international collaboration. Poland, with 6 documents and 65 citations, demonstrates a more robust international collaboration network, evidenced by its total link strength of 6. In contrast, Russia, despite producing a significant amount of research with 6 documents, shows less impact with 29 citations and a total link strength of zero, indicating isolation in the scientific community. Spain, also with 6 documents, has a moderate impact with 19 citations and a total link strength of 5, suggesting active collaborative participation but with potential for greater recognition. Bulgaria, with 5 documents, has a low number of citations (2) and a modest total link strength (1), indicating a need for greater visibility and global collaboration.

Table 2: Countries that publish the most in the area.

COUNTRY	DOCUMENTS	CITATIONS	TOTAL LINK STRENGTH
People's Republic of China	11	123	4
Poland	6	65	6
Russia	6	29	0
Spain	6	19	5
Bulgaria	5	2	1
Germany	5	71	10
Switzerland	5	65	10
Ukraine	5	14	2
Netherlands	4	57	9
Sweden	4	48	5

Source: The authors.

Germany and Switzerland, with 5 documents each, show high impacts of 71 and 65 citations, respectively, and total link strengths of 10, reflecting strong international collaboration and a robust presence in the scientific literature. Ukraine, with 5 documents and 14 citations, has a total link strength of 2, suggesting limited collaboration and lower impact. The Netherlands, with 4 documents and 57 citations, and Sweden, with 4 documents and 48 citations, have total link strengths of 9 and 5, respectively, indicating a strong collaborative presence and considerable impact in the scientific community. These data highlight the variation in involvement and impact of different countries in research on digital competencies in science education, with some countries showing a need to increase their visibility and international collaboration to improve their scientific impact.

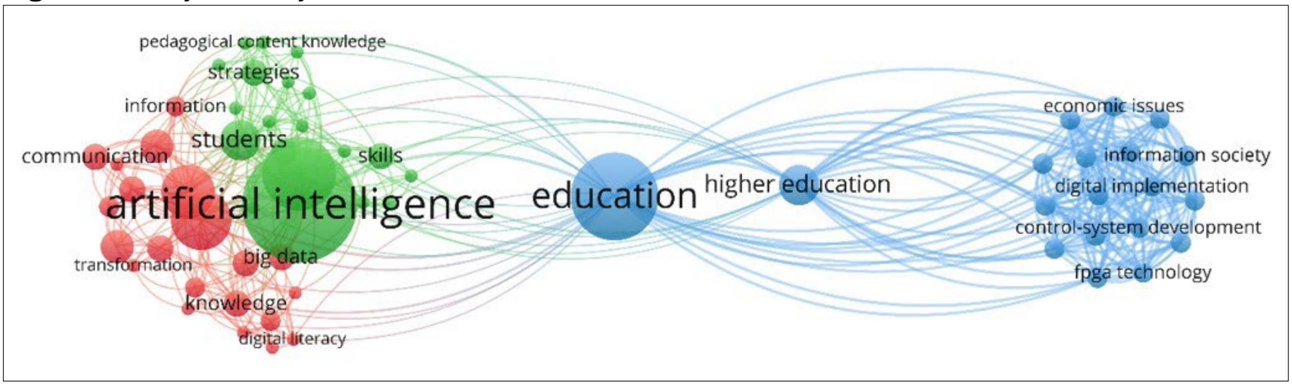
Co-occurrence Analysis

Using VOSviewer, the analysis was conducted considering the co-occurrence of all keywords. Initially, 397 keywords were identified from the total number of articles. To refine the analysis, synonymous words or variations in spelling were eliminated, retaining only the most recurring standard. A database was created to consolidate synonymous words and eliminate duplications, grouping singular and plural forms.

After these adjustments, the total number of keywords was reduced to 393. Of these, 71 keywords met the criterion of at least 2 co-occurrences. However, considering that the total number of keywords would significantly reduce by increasing the number of co-occurrences, it was decided to use 60 keywords to ensure a more robust and representative adjustment.

Considering the groupings made by the software, the keywords were analyzed within the context of the most cited articles, which helped to delineate the categories as presented in Figure 2 and discussed below.

Figure 2: Analysis of keyword co-occurrences, 2015–2024.



Source: The authors, using VOSviewer.

Category 1: Digital Competencies and Technologies in Education

The first category (Table 3) emphasizes digital competencies, evidenced by 8 occurrences and a total link strength of 32, reflecting the importance of effectively using digital technologies. The term "technology" predominates with 9 occurrences and a total link strength of 35, highlighting the development and implementation of technological systems in education. "Systems" has 5 occurrences and a total link strength of 19, reinforcing this trend.

"Digital skills" emerge with 4 occurrences and a total link strength of 17, indicating an interest in empowering students and teachers to navigate the digital environment. "Communication" with 4 occurrences and a total link strength of 10, and "digitalization" with 4 occurrences and a total link strength of 11, emphasize the integration of digital processes in educational systems. The presence of "ICT" with 4 occurrences and a total link strength of 15, along with "knowledge" with 4 occurrences and a total link strength of 18, highlights the need to understand and apply technologies in the educational context. "Curriculum" with 3 occurrences and a total link strength of 9, and "digital transformation" with 3 occurrences and a total link strength of 13, indicate the adaptation of educational content to new technological demands.

Terms like "information" with 3 occurrences and a total link strength of 15, "model" with 3 occurrences and a total link strength of 14, and "digital literacy" with 2 occurrences and a total link strength of 9, denote specific areas of interest and research. "Teachers" registers 5 occurrences and a total link strength of 8, while "preservice teachers" has 2 occurrences and a total link strength of 11, highlighting the continuous training and preparation of educators for the effective use of digital technologies. "Big data" with 4 occurrences and a total link strength of 9 reflects the interest in large volumes of data in education. "Attitudes" with 2 occurrences and a total link strength of 10 and "social media" with 2 occurrences and a total link strength of 7 highlight contemporary and behavioral aspects of technology integration. "Future" with 2 occurrences and a total link strength of 10 and "transformation" with 2 occurrences and a total link strength of 10 suggest a forward-looking vision and continuous evolution in the educational context.

The first category reveals broad interests and trends, highlighting key areas of development and implementation, as well as the preparation of students and educators for an increasingly digital educational environment.

Table 3: Analysis of Keywords in Category 1 of VOSviewer.

KEYWORD	OCCURRENCES	TOTAL LINK STRENGTH
technology	9	35
digital competence	8	32
systems	5	19
teachers	5	8
big data	4	9
communication	4	10
digital skills	4	17
digitalization	4	11
ict	4	15
knowledge	4	18
curriculum	3	9
digital transformation	3	13
information	3	15
model	3	14
attitudes	2	10
digital literacy	2	9
future	2	10
literacy	2	13
preservice teachers	2	11
social media	2	7
transformation	2	10

Source: The authors.

Category 2: Artificial Intelligence and Innovation in Education

The second category (Table 4) highlights artificial intelligence as a dominant topic, with 17 occurrences and a total link strength of 47, indicating significant interest in the application of AI to enhance teaching and learning processes. The keyword "competence" appears with 11 occurrences and a total link strength of 41, demonstrating a broad concern with the development of various competencies. The relevance of "students" is evident with 6 occurrences and a total link strength of 28, suggesting a central focus on students' needs and engagement. Educational "strategies," with 4 occurrences and a total link strength of 15, indicate a search for innovative methods to engage and educate students more effectively.

Terms like "machine learning" with 4 occurrences and a total link strength of 17 and "skills" with 4 occurrences and a total link strength of 17 highlight the interest in specific AI techniques and the development of related skills. "Engagement" (2 occurrences, total link strength of 10) and "performance" (2 occurrences, total link strength of 10) reflect concerns with effectiveness and motivation in the educational environment. The presence of "innovation" with 2 occurrences and a total link strength of 11 and "impact" with 2 occurrences and a total link strength of 13 suggests attention to the effects of new technologies in education.

"Framework" (2 occurrences, total link strength of 9) and "systematic review" (2 occurrences, total link strength of 13) indicate a structured and evidence-based approach to educational research. Additionally, "professional development" with 2 occurrences and a total link strength of 9 and "teacher education" with 2 occurrences and a total link strength of 11 underscore the importance of continuous teacher training for effective implementation of educational technologies. "Pedagogical content knowledge" (2 occurrences, total link strength of 12) and "self-determination theory" (2 occurrences, total link strength of 9) reflect interest in pedagogical theories and practices that support technological integration.

Terms like "robotics" (2 occurrences, total link strength of 7) and "natural language processing" (2 occurrences, total link strength of 8) highlight specific areas of AI application in education. "TPACK" (2 occurrences, total link strength of 12) represents the integration of technological, pedagogical, and content knowledge, essential for modern education.

The second category reveals a substantial focus on artificial intelligence and innovation in education, emphasizing the importance of developing competencies, engaging students, and training educators for an increasingly technological and innovative educational environment.

Table 4: Analysis of Keywords in Category 2 of VOSviewer.

KEYWORD	OCCURRENCES	TOTAL LINK STRENGTH
artificial intelligence	17	47
competence	11	41
engagement	2	10
framework	2	9
impact	2	13
innovation	2	11
machine learning	4	17
natural language processing	2	8
pedagogical content knowledge	2	12
perceptions	2	12
performance	2	10
professional-development	2	9
robotics	2	7
self-determination theory	2	9
skills	4	17
strategies	4	15
students	6	28
systematic review	2	13
teacher education	2	11
tpack	2	12

Source: The authors.

Category 3: Development and Implementation of Technologies in Education

The third category (Table 5) highlights the strong presence of the theme "education" with 13 occurrences and a total link strength of 81, indicating an intense focus on the integration of technology in the educational context. "Higher education" registers 6 occurrences and a total link strength of 67, reflecting interest in how technologies are applied and developed in universities and higher education institutions.

The emphasis on "digital implementation" and "control system development," both with 3 occurrences and a total link strength of 54, demonstrates significant interest in the technical and practical aspects of applying technologies in education, aimed at developing specific technological solutions that can be implemented in educational environments. Terms like "electronics" and "FPGA technology" (Field Programmable Gate Array), each with 3 occurrences and a total link strength of 54, indicate an interest in advanced technologies and their practical application in education.

"Information society" and "professional communities," also with 3 occurrences and a total link strength of 54, reflect the importance of understanding the impact of technologies on society and fostering collaboration among professionals in the educational field. Other terms like "economic issues" (3 occurrences, total link strength of 54), "industry" (3 occurrences, total link strength of 54), and "telecommunications" (3 occurrences, total link strength of 54) suggest an interest in the intersection between education and economic, industrial, and technological development.

The presence of "linear-accelerator" and "simulator" (both with 3 occurrences and a total link strength of 54) indicates research in technologies that can be used to create advanced and simulated learning environments. Additionally, "tailored optical-fibers," "tesla cavity controller," and "probe" (all with 3 occurrences and a total link strength of 54) denote the exploration of cutting-edge technologies that can potentially revolutionize teaching and learning methods. Terms like "reagent" and "water" (both with 3 occurrences and a total link strength of 54) may indicate research in specific areas of science education where the use of advanced technologies is crucial.

Table 5: Analysis of Keywords in Category 3 of VOSviewer.

KEYWORD	OCCURRENCES	TOTAL LINK STRENGTH
education	13	81
higher education	6	67
control-system development	3	54
development	3	54
digital implementation	3	54
economic issues	3	54
electronics	3	54
fpga technology	3	54
industry	3	54
information society	3	54
linear-accelerator	3	54
probe	3	54

professional communities	3	54
reagent	3	54
simulator	3	54
tailored optical-fibers	3	54
telecommunications	3	54
tesla cavity controller	3	54
water	3	54

Source: The authors.

The third category reveals a significant focus on the development and implementation of specific technologies in the educational context, with particular interest in their application in higher education. The research spans from technical and practical aspects to the economic and societal impact of technologies in education.

The integrated analysis reveals that the first category emphasizes the need to develop basic and advanced digital competencies among students and teachers for a digitalized educational environment. The second category highlights the exploration of emerging technologies, such as artificial intelligence and machine learning, to innovate and improve educational processes, focusing on personalized learning and increased student engagement. The third category underscores the importance of developing and implementing specific technologies in the educational context, especially in higher education, indicating the need for integrated technical and practical solutions in educational practices.

These categories outline a scenario of strong technological integration in education, emphasizing digital competencies, technological innovations, and practical applications. The general trend suggests continuous evolution and adaptation to technological changes, while the identified gaps indicate areas for future research, such as specific strategies for different educational contexts, evaluation of the impact of these technologies on learning, and creation of educational models that integrate these emerging technologies.

The VOSviewer analysis, considering the focus on science education, highlights the importance of empowering educators and students, exploring emerging technologies, and developing practical solutions applicable in the educational environment. Specifically, AI presents significant potential to contribute to the development of digital competencies in education, considering the following points:

a. Personalized Learning: Creation of personalized learning systems that adapt content and teaching pace to individual student needs.
b. Immediate Feedback and Continuous Assessment: Availability of continuous assessments and immediate feedback, allowing adjustments in the teaching process based on student performance.
c. Educational Data Analysis: Analysis of large volumes of data to identify gaps and strengths in students' digital competencies, enabling personalized interventions.
d. Development of Interactive Content: Development of interactive and immersive educational content, such as gamification and simulations, that facilitate the learning of digital competencies.
e. Support for Teaching Digital Skills: Offering personalized tutorials and practical activities to develop technological skills.
f. Innovation and Research: Identification of research gaps, contributing to new pedagogical approaches and educational innovation.

g. Continuous Teacher Training: AI tools can provide personalized training and resources for educators, improving their digital competencies and teaching practices.

Strategic Coordinates Diagrams

The data were imported into SciMAT with subsequent elimination of synonyms or variations in writing (singular and plural), maintaining the most recurring standard. The chosen unit of analysis was keywords, considering the roles of author, source, and additional (authorRole=true, sourceRole=true, addedRole=true). The type of network analyzed was co-occurrence, using the equivalence index as the normalization measure. For cluster formation, the simple centers algorithm was applied, establishing a maximum cluster size of 4 and a minimum of 1. The selected evolution measure was the Jaccard index, while the overlap measure used was the equivalence index. These configurations aim to ensure a detailed and accurate analysis of term relationships.

SciMAT generated Strategic Coordination Diagrams that provide an intuitive visualization of the evolutionary state of research themes, offering an understanding of the field of study, where the nodes represent thematic clusters, and the associated numbers indicate the volume of literature related to each theme, reflecting their interest and relevance. The horizontal axis evaluates centrality, highlighting the strength of association of a theme with others within the research field. The greater the centrality, the more central the position of the theme and the more strongly it relates to other areas. The vertical axis represents density, indicating the degree of association between keywords within a theme. Higher density suggests a more robust internal connection and a more advanced stage of thematic development.

The intersection of these axes divides the plane into four distinct quadrants, each providing information about the analyzed themes. The upper-left quadrant generally hosts well-developed themes but possibly isolated from the others. Meanwhile, the lower-left quadrant highlights emerging or declining themes that need more attention and investigation. On the other hand, the upper-right quadrant reveals central and consolidated themes with strong connections to other themes, often representing leading research areas. These are identified by highly cohesive clusters associated with prominent keywords. Finally, the lower-right quadrant is occupied by important but underdeveloped themes, offering opportunities for future investigations and deepening.

Thus, the analyses performed in SciMAT form clusters around the keywords with the highest incidence in the studies (Petrillo Pires de Araújo et al., 2023). These clusters represent sets of highly interconnected keywords within the analyzed literature, reflecting thematic associations and enabling the identification of emerging trends and relationships between different themes. Nodes, in turn, are individual elements in a network diagram. In SciMAT, nodes generally represent keywords, while clusters are groupings of these nodes.

The data from the analysis are summarized in Table 6, where the following information was used: a) Cluster: a set of highly interconnected keywords within the analyzed literature, reflecting thematic associations. They can represent specific research topics or relevant concepts in the field of study. Analyzing these clusters allows identifying emerging trends and relationships between different themes. b) Centrality: a measure of the centrality of each cluster, highlighting its importance and connection to other themes within the research field. c) Centrality range: the range of centrality values covered by the clusters, allowing relative comparison between them. d) Density: indicates the degree of connection between keywords within the theme. e) Density range: the range of density values covered by the clusters, showing the internal cohesion of the themes. f) Documents: the total number of documents associated with each cluster. g) h-index: the h-index calculated for each cluster, representing the number of documents in the cluster (h) that have received at least h citations. h) Citations: the total number of citations received by the documents within each cluster, indicating the relevance and impact of the theme in the scientific community (Shen et al., 2023).

Table 6: Clusters found in SciMAT.

N	CLUSTER	CENTRALITY	CENTRALITY RANGE	DENSITY	DENSITY RANGE	DOCUMENTS	H-INDEX	CITATIONS
1	ARTIFICIAL INTELLIGENCE	15.11	1	13.63	0.67	14	6	99
2	PRESER-VICE-TEACHERS	12.88	0.67	14.58	1	3	2	23
3	COMMUNICA-TION	9.97	0.33	8.02	0.33	3	1	1

Source: The authors.

Table 7 presents the keywords and a summary of the analysis for each category.

Table 7: Summary of the category analysis.

N	CLUSTER	KEYWORDS [DOCUMENTS]	DESCRIPTION AND ANALYSIS
1	ARTIFICIAL INTELLI-GENCE	artificial intelligence [20] competence [11] technology [9] skills [5]	Bibliometric data indicate that “digital competence” and “technology” are central terms, both with 9 occurrences, highlighting the importance of equipping students and teachers with digital competencies. The presence of “systems” (6 occurrences) and “communication” (5 occurrences) reinforces the need to integrate technologies into educational processes, both from a technical standpoint and in effective use to facilitate collaboration and information exchange. The recurrence of “digital skills” (5 occurrences) underscores the relevance of developing specific skills for efficient navigation and use of digital technologies. This category evidences a comprehensive approach to preparing individuals for a digital educational environment, where competence in information and communication technologies is essential.

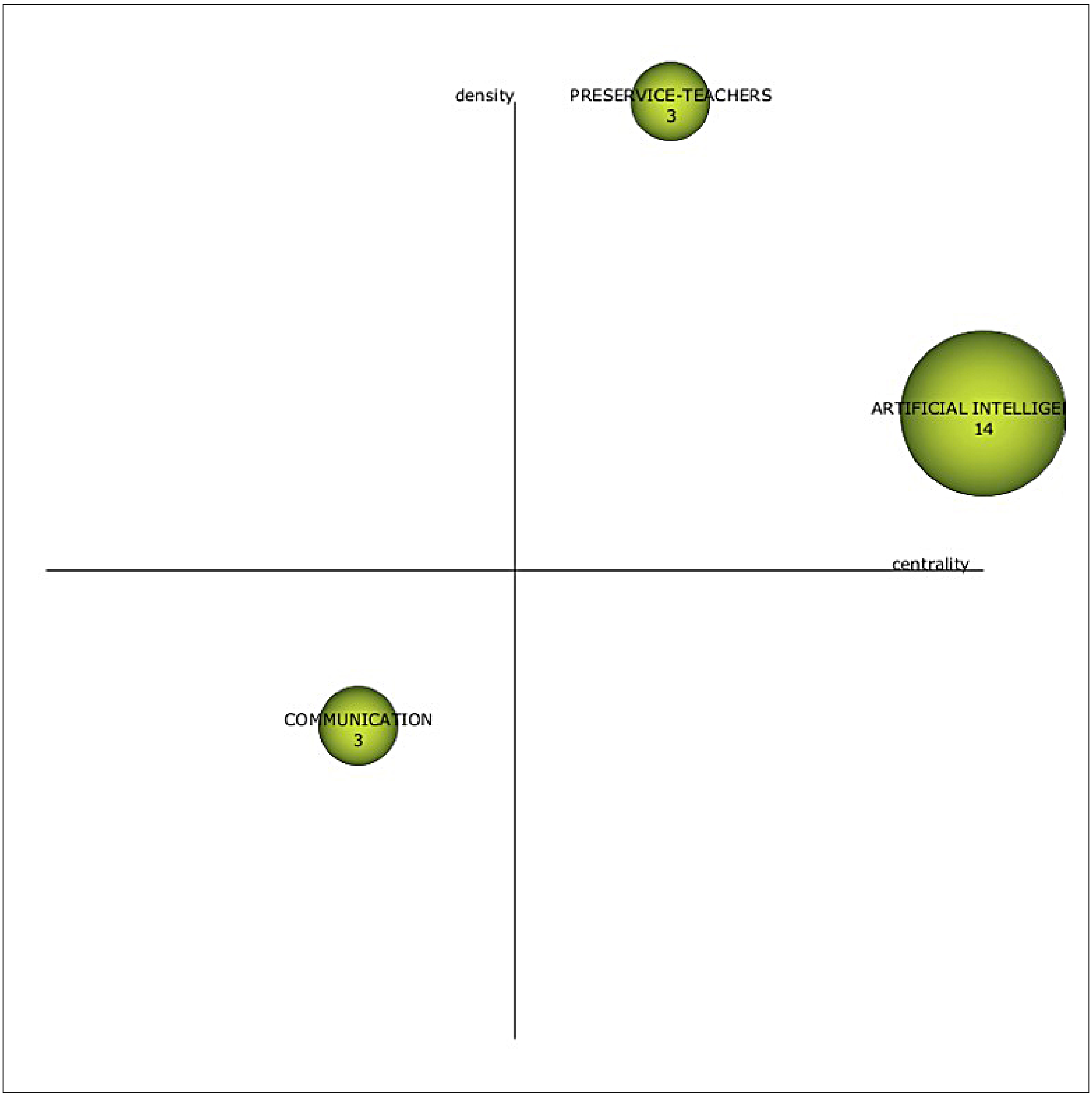
2	PRESER-VICE-TEACH-ERS	model [4] preservice-teachers [4] innovation [3] proposal [2]	“Artificial intelligence” stands out with 20 occurrences, evidencing substantial interest in its application to enhance educational processes. The term “competence” appears 11 times, indicating a focus on developing various competencies through the use of AI. “Innovation” with 3 occurrences suggests a search for new pedagogical approaches that incorporate AI to improve teaching and learning. The terms “model” with 4 occurrences and “proposal” with 2 occurrences reflect research dedicated to developing and testing new AI-based educational models. This category suggests an in-depth exploration of how AI can transform education, from process automation to the creation of personalized and innovative learning experiences.
3	COMMUNICA-TION	digital-competence [9] systems [6] communication [5]	“Digital competence” and “technology” each appear with 9 occurrences, indicating ongoing interest in the development and implementation of digital technologies. The presence of “systems” with 6 occurrences and “communication” with 5 occurrences highlights the importance of a robust technological infrastructure and effective communication skills for the successful implementation of these technologies in education. Additional terms such as “skills” with 5 occurrences and “innovation” with 3 occurrences reinforce the need for continuous development of competencies and innovative practices in teaching. This category reflects research focused on creating an educational environment that effectively incorporates digital technologies, promoting both the necessary infrastructure and the interpersonal and technical skills required for successful implementation of these technologies.

Source: The authors with SciMAT.

The analysis of the strategic coordinates diagram (Figure 3) reveals the presence of the categories “Artificial Intelligence” and “Preservice-Teachers” in the upper right quadrant. These categories exhibit high centrality, indicating strong thematic connections with other areas in the research field. The “Preservice-Teachers” category is positioned higher on the diagram, reflecting greater internal density and cohesion among its associated keywords. In contrast, “Artificial Intelligence” appears further to the right, denoting higher centrality and broader integration with other research themes, despite slightly lower internal density. Both categories are associated with a substantial number of documents and present a notable h-index, indicating significant impact within the scientific community.

In the lower left quadrant, the "Communication" category is located, characterized by both low density and low centrality. This positioning suggests limited thematic cohesion and weaker connections to other research areas. The smaller number of associated documents and a modest h-index reinforce its relatively reduced influence compared to the more prominent categories in the upper right quadrant.

Figure 3: Strategic Coordinates Diagrams for the total number of documents.



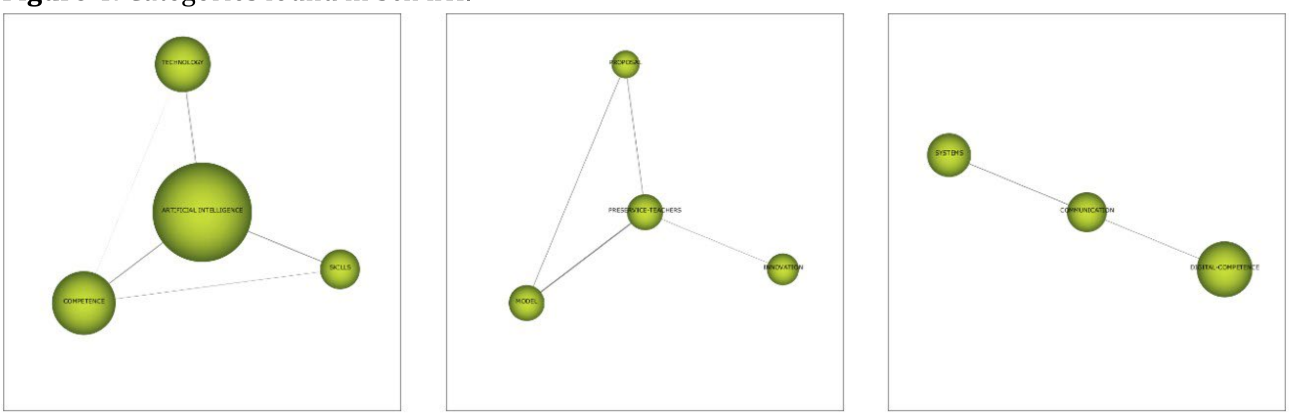
Source: The authors, using SciMat.

Figure 4 shows that the category "ARTIFICIAL INTELLIGENCE" focuses on the application of AI in various areas, being mentioned in 20 documents. Terms like "competence," "technology," and "skills" indicate an interdisciplinary approach, exploring the intersection between AI and digital competencies. This category presents high centrality (15.11) and density (13.63), with an h-index of 6 and 99 citations, demonstrating significant impact in the academic community.

The category "PRESERVICE-TEACHERS" focuses on teacher training, emphasizing innovative aspects. The keyword "preservice-teachers" appears in 4 documents, while "model," "innovation," and "proposal" suggest investigations into innovative models for initial teacher training. This category shows high centrality (12.88) and density (14.58), with an h-index of 2 and 23 citations, significantly contributing to the field of teacher education.

The category "COMMUNICATION" addresses digital communication and associated digital competence, with "digital-competence" mentioned in 9 documents. Terms like "systems" and "communication" indicate interdisciplinary investigation. This category has moderate centrality (9.97) and density (8.02), with 3 documents, an h-index of 1, and only 1 citation, suggesting the need for further development to increase its academic relevance.

Figure 4: Categories found in SciMAT.



Cluster 1: ARTIFICIAL INTELLIGENCE	Cluster 2: PRESERVICE-TEACHERS	Cluster 3: COMMUNICATION

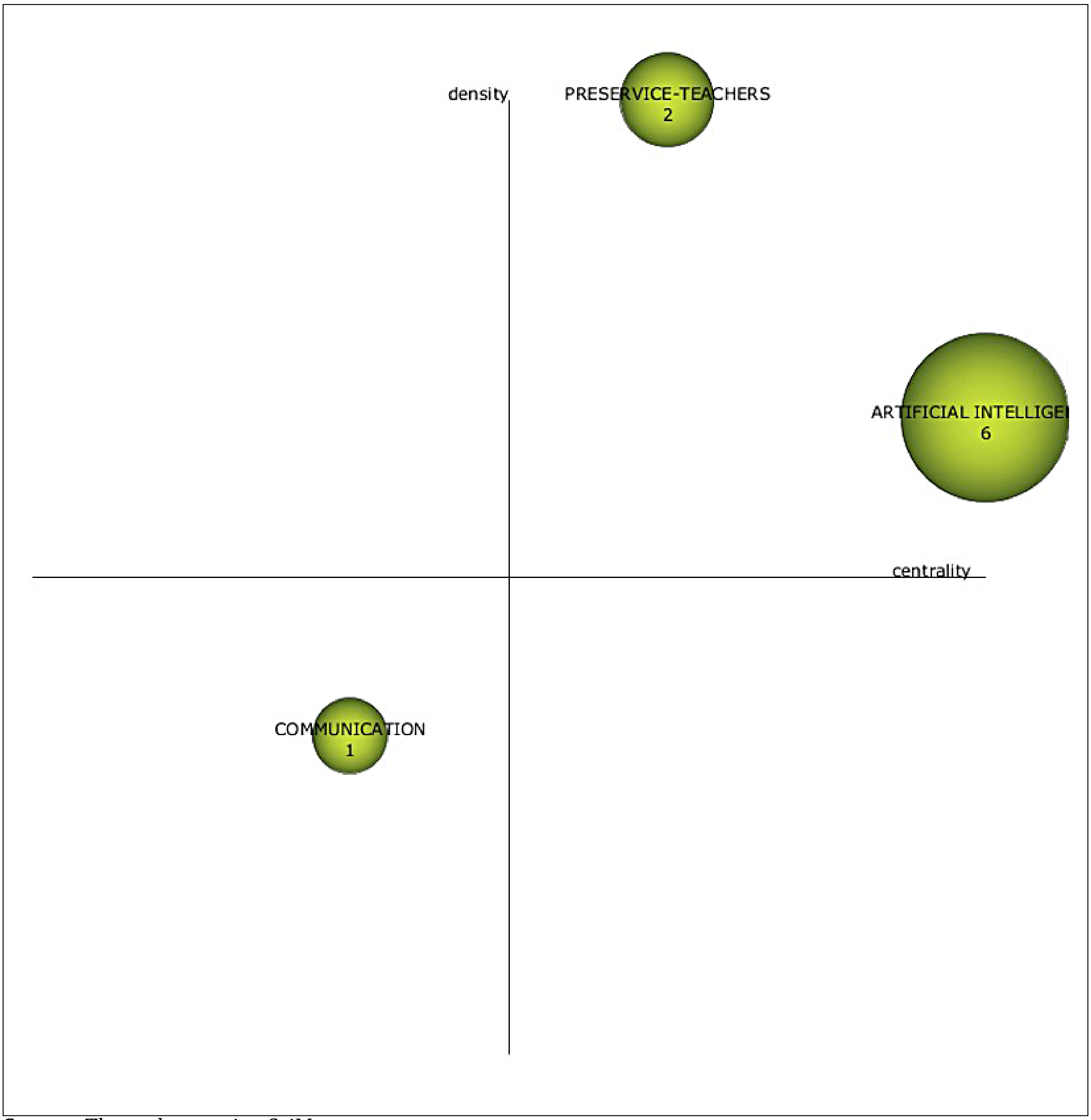
Source: The authors, using SciMat.

The analysis of the categories in different quadrants of the strategic coordinates diagram reveals significant variations in bibliometric metrics, such as the total number of documents, the h-index, and the sum of citations.

In the upper right quadrant, the categories "Artificial Intelligence" and "Preservice-Teachers" stand out with 14 and 3 documents, respectively, presenting h-indices of 6 and 2, suggesting substantial relevance in the scientific community (Figure 5). The "Artificial Intelligence" category received 99 citations, while "Preservice-Teachers" obtained 23 citations, indicating significant influence in terms of scientific production and academic impact (Figure 6).

In the lower left quadrant, the "Communication" category has only 3 documents, an h-index of 1 (Figure 5), and a sum of citations of 1 (Figure 6), reflecting lower scientific production and relatively limited impact in the scientific community compared to the categories in the upper quadrants.

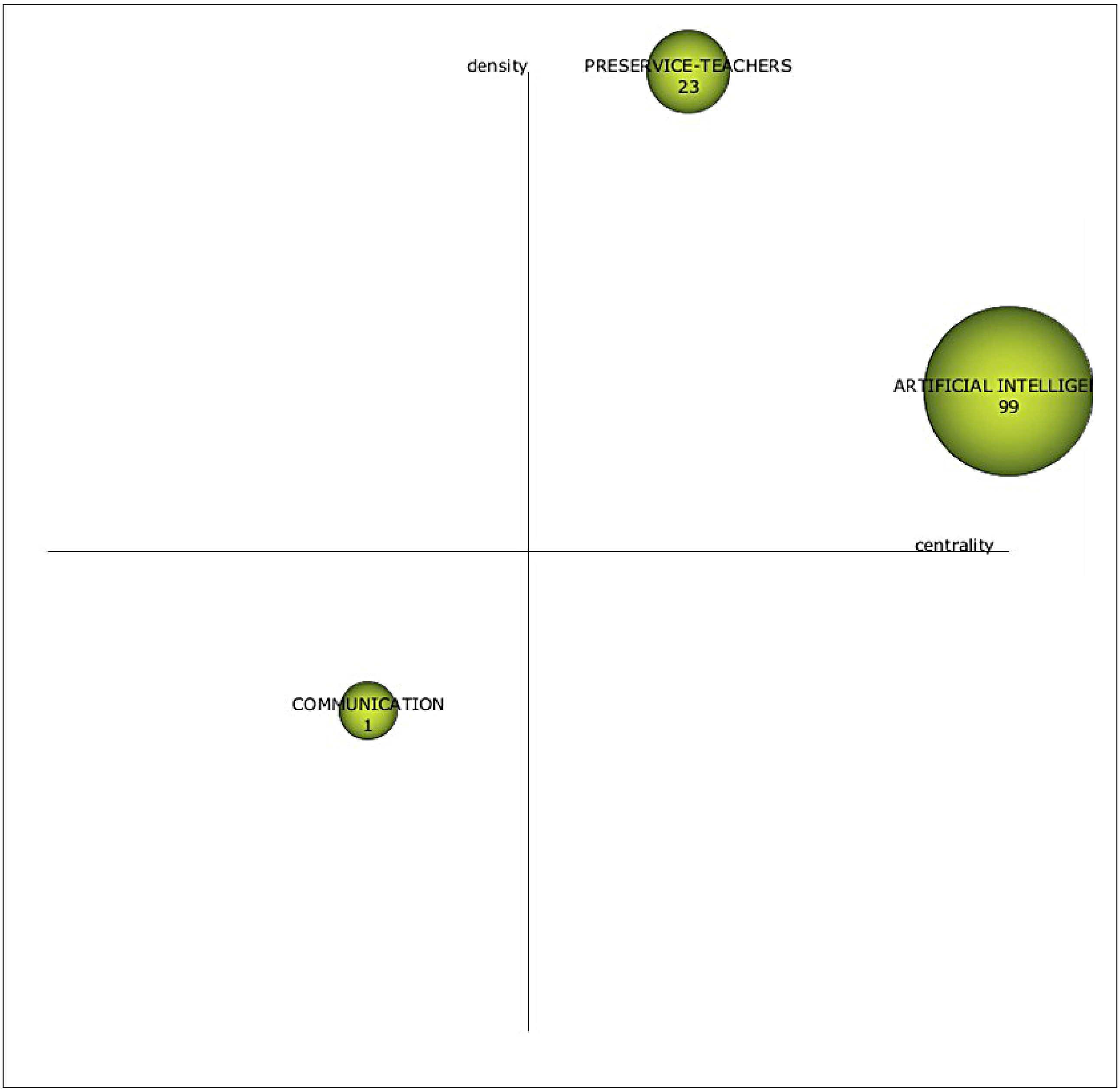
Figure 5: Strategic coordinates diagram for the h-index.



Source: The authors, using SciMat.

These analyses emphasize the importance of the categories in the upper right quadrant in terms of research quantity and impact. "Artificial Intelligence" and "Preservice-Teachers" represent leading research areas, while "Communication" in the lower left quadrant suggests an area that may require further development to increase its academic relevance and impact.

Figure 6: Strategic diagram for total citations.



Source: The authors, using SciMat.

The integrated analysis of the three categories reveals trends in research on digital competencies, technology in education, artificial intelligence, innovation, and the development and implementation of technologies. The consistency of terms like “digital competence” and “digital skills” across all categories highlights the growing need to develop technological skills in students and teachers. The recurrence of “technology” and “systems” underscores the importance of robust technological infrastructure to improve teaching and learning processes.

Teacher training is another critical area, evidenced by the presence of “preservice teachers,” indicating the need to prepare future educators to use digital technologies and AI. Initial and ongoing teacher training is essential for the successful implementation of these technologies. Additionally, terms like “innovation,” “model,” and “proposal” reflect the continuous effort to develop and test new pedagogical approaches, with AI being a key tool for creating more personalized and effective learning experiences.

"Artificial intelligence" stands out as a dominant theme, showing substantial interest in how AI can be applied to improve education by offering possibilities for process automation, personalized learning, and the development of new competencies. The importance of communication skills for effective collaboration and the use of digital technologies is underscored by the recurrence of the term "communication."

Overall, the research signals a focus on the importance of digital competencies, technological integration, teacher training, innovation, and the application of artificial intelligence in education. The trends suggest that research is advancing to create an educational environment that meets the demands of an ever-evolving digital world, emphasizing the development of technological skills and new pedagogical approaches..

Final Considerations

The analyses from VOSviewer and SciMAT converge in identifying trends, gaps, and possibilities for future research in the area of digital competencies and technology in education, focusing on AI integration. Both analyses highlight the growing need to develop digital competencies among students and teachers for a digitized educational environment. The consistency of terms like "digital competence" and "digital skills" across all categories underscores the importance of these technological skills.

Teacher training emerges as a critical area, with terms like "preservice teachers" indicating the need to prepare educators to use digital technologies and AI. Continuous teacher training is essential for the successful implementation of these technologies, a point underscored by both analyses.

The integration of emerging technologies such as AI and machine learning is highlighted as a significant trend. AI is seen as a key tool to personalize learning, automate assessments, and create interactive content, enhancing student motivation and engagement. The analyses also point to the need for robust technological infrastructure and effective communication skills to implement these technologies in the educational context.

Despite these trends, notable research gaps exist. The analysis identified "Communication" as a domain still needing more development, highlighting a lack of effective approaches to promote digital communication skills among educators and students. The need for robust educational policies promoting continuous training and effective ICT use, ensuring data security and privacy, is an area requiring attention.

Future research possibilities include personalizing digital competency development, adapting content and teaching methods to students' specific needs. Creating AI-based learning platforms that continuously assess student progress and adjust content as needed is a promising area. Rigorous evaluation of the effectiveness of these interventions in improving digital competencies and student motivation is essential.

Moreover, analyzing large volumes of educational data using AI can identify deficiencies and strengths in developing digital competencies, allowing for more precise, evidence-based interventions. Research can also explore developing interactive and immersive educational content, such as gamification and simulations, which facilitate learning digital competencies.

Ongoing educator training with AI tools providing personalized training and resources is another potential research area. Evaluating the effectiveness of these training programs and integrating AI into educators' professional development programs are promising paths.

Finally, AI can foster research and innovation by analyzing trends in the scientific literature, suggesting study directions, and promoting collaboration between institutions and research groups. Longitudinal studies tracking the impact of AI on developing digital competencies over time are crucial to understanding and continually improving educational practices.

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