Multimodal Technologies and Interaction

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Review

Combining Artificial Intelligence with Augmented Reality and Virtual Reality in Education: Current Trends and Future Perspectives

Georgios Lampropoulos [1,2,3]

[1] Department of Applied Informatics, School of Information Sciences, University of Macedonia, 54636 Thessaloniki, Greece; glampropoulos@uom.edu.gr
[2] Department of Education, School of Education, University of Nicosia, Nicosia 2417, Cyprus
[3] Department of Preschool Education, School of Education, University of Crete, 74100 Rethymno, Greece

Abstract: The combination of artificial intelligence with extended reality technologies can significantly impact the educational domain. This study aims to present an overview regarding the combination of artificial intelligence with augmented reality and virtual reality technologies and their integration in education through an analysis of the existing literature. Hence, this study examines 201 documents from Scopus and the Web of Science (WoS). This study focuses on examining the basic characteristics of the document collection, highlighting the most prevalent themes, areas, and topics, exploring the thematic evolution of the topic, revealing current challenges and limitations and on identifying emerging topics and future research directions. Based on the outcomes, a significant annual growth rate (60.58%) was observed indicating the increasing interest in the topic. Additionally, the potential of combining artificial intelligence with virtual reality and augmented reality technologies to provide personalized, affective, interactive, and immersive learning experiences across educational levels in both formal and informal settings supporting both teachers and students arose. Therefore, through this combination, intelligent tutoring systems (ITSs), which offer behavioral, cognitive, and social personalization, have a virtual presence, and can effectively be used as tutors or peer learners, can be created. Such ITSs can be characterized as affective and social entities that can increase students' learning performance, learning motivation, and engagement and promote both self-directed learning and collaborative learning. This study also highlights the need to examine how the physical presence that characterizes some new technologies compares to the virtual presence that extended reality technologies offer in terms of overall learning outcomes and students' development.

Keywords: artificial intelligence; AI; virtual reality; augmented reality; mixed reality; extended reality; metaverse; intelligent tutoring systems; review; bibliometric analysis; scientific mapping

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1. Introduction

Digital technologies play a vital role in the educational process, as their integration into teaching and learning can yield several changes to the educational domain [1]. As students grow up with technological applications surrounding them, their educational interests and needs have drastically changed [2]. Specifically, students pursue to be actively involved in the educational process, they prefer learning based on hands-on experiences and real-world examples, and are in search of interactive, engaging, and personalized learning environments [3].

Personalized learning is an integral part of 21st-century education [4] as learning constitutes both a personal and a collaborative experience through which one can improve their knowledge and skills, expand their perspectives, and increase their understanding on subject matter [5]. Engaging students in technology-enhanced learning is vital to achieve personalized learning [6]. Since personalized learning can improve students' learning outcomes [7], emphasis has been put on the use of new technologies and how they affect personalized learning. For example, studies have focused on how intelligent tutoring systems [8], recommender systems [9], intelligent web-based learning systems [10], and artificial intelligence [11], among other technologies, can support and promote personalized learning. Additionally, studies have highlighted the role of motivation [12], interactivity [13], engagement [14], embodiment [15], and immersion [16] in education and in improving learning outcomes. Among the different technologies, the combination of artificial intelligence with extended reality technologies has shown great potential in transforming and enhancing the educational domain and in helping satisfy the new educational requirements [17].

The integration of artificial intelligence into various domains is increasing rapidly [18]. Among the different domains, the use of artificial intelligence in education has shown great potential to improve the educational process, by transforming and enriching traditional practices and approaches and by promoting the redesign of culture, cognition, and knowledge [19–22]. Artificial intelligence systems are inspired by the human nervous system and are characterized by their adaptability and their ability to learn from different sources as well as to reason and make decisions in an autonomous, sophisticated, and rational manner [23–25]. As a result, artificial intelligent systems mimic the way humans act, think, and communicate and, consequently, simulate human intelligence [26,27]. Recent studies have explored and highlighted the role, advantages, and disadvantages of adopting and integrating artificial intelligence in education and have revealed current challenges and issues [19,28–34]. As a result, and due to its potential, the field of artificial intelligence in education is rapidly advancing [35,36].

Extended reality technologies are increasingly being examined in educational settings. These technologies offer new reality formats and consist of virtual reality, augmented reality, and mixed reality [37]. In this context, the reality–virtuality continuum describes a continuum in which one end refers to the real environment and is closer to augmented reality while the other end refers to the virtual environments and is closer to virtual reality, and somewhere in between, a mixed reality exists in which both real and virtual objects and environments co-exist [38]. Specifically, virtual reality involves, either real or simulated, virtual environments that perceptually surround, immerse, and engage users by simulating their physical presence within them [39–42]. These fully virtual environments immerse users and separate them from the real environment while offering experiences that are characterized by high levels of immediacy, interactivity, immersion, and involvement [40,43,44]. Within virtual reality environments, emphasis is put on integrating social and psychological aspects so that the overall experiences and environments can be perceived as real [45]. As a result, virtual reality technology created an "all-inclusive, sensory illusion of being present in another environment" [46]. Furthermore, augmented reality enables users to interact with both the virtual and digital worlds in real time by enriching users' physical environment with virtual content, information, and objects that users can perceive through their senses and interact with using multiple sensory modalities [47–51]. Due to their potential to transform the educational domain, recent studies that have carried out literature reviews on the use of virtual reality [3,52–54], augmented reality [55–59], and mixed reality [60–62] technologies as well as the metaverse [63–65] have examined the use of extended reality technologies in educational settings and have revealed the related benefits, drawbacks, and implications that arise when using them in teaching and learning activities.

Based on the aforementioned, many recent studies have been carried out that explored the use of artificial intelligence, augmented reality, virtual reality, and the metaverse in education. Although these studies provide meaningful insights regarding their integration in education, as their use in educational settings and the research into these technologies are rapidly increasing, there is a clear need to map and analyze the existing literature to identify key topics and thematic areas regarding the current state of the art and future research directions. Consequently, this study aims to offer an overview of the existing literature regarding the combination of artificial intelligence with augmented reality and virtual reality in education and identify future research areas. This study adds to the existing body of knowledge by analyzing the basic characteristics of the documents (e.g., publication frequency, citation count, authors, sources, countries, affiliations, etc.), by identifying the most advanced research areas and those that are still in their early stages, by revealing the most prominent trends, themes, and topics, and by offering future research directions based on the limitations and challenges identified in the literature.

2. Materials and Methods

Due to the scope of this study, as it looks into the use of artificial intelligence within augmented reality and virtual reality environments and focuses on examining the topic from an interdisciplinary approach, a bibliometric analysis of the existing literature was carried out. This approach is regarded as appropriate to examine the current state of the art on specific topics, particularly, when they are looked at from a more general perspective [66]. As this study aims to present the current trends and future perspectives regarding the integration of artificial intelligence in extended reality environments across domains, to conduct a rigorous and valid analysis of the existing literature, the guidelines specified by Donthu et al. [67] and Gusenbauer and Haddaway [68] were followed. Additionally, the method presented by Aria and Cuccurullo [69] was followed to carry out the bibliometric analysis. Particularly, the open-source R package Bibliometrix [69] was adopted and used. Additionally, to further explore and analyze the document collection, VOSviewer [70] and topic modeling through Latent Dirichlet Allocation (LDA) [71] were also used. Both tools are validated and widely accepted as effective and suitable means to carry out reproducible and valid scientific mapping and bibliometric analysis studies.

A key component in any study that aims to examine and present the current state of the literature is the use of highly regarded databases to identify relevant documents. Following the outcomes of recent studies that revealed Scopus and Web of Science as the top databases based on the quality of indexed documents, their covering various topics and disciplines, and their being widely used to carry out similar studies [72,73], the specific two databases were selected. Another crucial part in opting to use these databases, besides their being widely used in similar studies, was the ability to use the related information extracted from them with the tools used in this study [69]. Data from other sources could also be used but it would require manual adjustments that could affect the reproducibility of this study. Hence, this study examined documents only from Scopus and Web of Science.

As this study aimed to provide an overview of the existing literature across domains, the only limitation set when searching for relevant documents was for them to be written in English. No other limitations or filters were utilized in the query. Given the scope and perspective of this study, keywords relevant to each topic were identified and focus was put on intelligent systems and how they are being integrated in education. In the case of artificial intelligence, the general term and its abbreviation was used, while chatbots, tutoring systems, and assistants were identified as key areas within the literature. The selection of keywords regarding extended reality technologies and the educational context was based on those of other related studies [3,59]. Additionally, after testing various combinations of keywords, the following set of keywords was selected and used: ("artificial intelligence" OR "ai" OR "chatbot*" OR "chat bot*" OR "automated tutor*" OR "personal tutor*" OR "intelligent tutor*" OR "intelligent agent*" OR "adaptive educational system*" OR "adaptive learning system*" OR "intelligent tutoring system*" OR "virtual assistant*" OR "personal assistant*" OR "intelligent assistant*" OR "ai assistant*") AND ("augmented reality" OR "AR" OR "virtual reality" OR "VR" OR "mixed reality" OR "MR" OR "extended reality" OR "XR" OR "metaverse") AND ("education" OR "teach*" OR "student*" OR "learner*" OR "universit*" OR "school*" OR "classroom*" OR "course*"). The reason for using the specific query was twofold. First, to identify all potentially relevant documents, acronyms related to the technologies that this study focused on were used despite their returning additional documents that were not relevant and were therefore eliminated. This decision resulted in an increased number of documents being identified as potentially relevant at the initial stage and their being removed afterwards. However, the tradeoff was that all related documents were identified. Second, as this study did not focus on a specific educational level nor on a specific type of artificial intelligence or extended reality technology to present the general state of this topic, no specialized keywords were used as they could provide explicit directions to specific domains, functions, or use cases. This decision resulted in a more general representation of the literature to be presented and for a larger number of documents to be examined to provide a more thorough and complete depiction of the state of the art.

The specific set of keywords was used to search for relevant documents on Scopus and Web of Science on a topic level. Hence, the set of keywords would have to match either the title, abstract, or keywords of a document for it to be identified as potentially relevant to the topic. Studies that provide a thorough analysis of the existing literature should also be reproducible, transparent, accurate, and valid. For this reason, the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement [74] was followed to ensure that all the required criteria in terms of quality and rigor were met. PRISMA is a widely used and validated method that is commonly used in systematic literature review studies and in bibliometric reviews [74].

Figure 1 showcases the complete PRISMA flowchart. Specifically, the aforementioned query was last used in December 2024 to search for suitable documents in Scopus and Web of Science. The query returned 4124 documents from Scopus and 1335 documents from Web of Science. As a result, the initial document collection consisted of 5459 documents. As both of these databases are used by most quality outlets, they do index some common documents. Hence, duplicates were identified and removed both automatically and manually. A total of 1061 duplicates were found and removed and 1919 documents were automatically removed using a keyword search as they were outside the scope of this study. Hence, 2479 documents remained in the document collection and were further examined for consideration manually. Specifically, 363 documents were removed because they were proceedings books, 118 were removed as they were books, 11 were removed since they were short communications, 14 were removed as they were editorials, 13 were removed due to their being erratum, and 18 were removed as they were retracted documents. Given the scope of this study, for a document to be regarded as relevant, it had to meet the inclusion criteria which were for it to focus on the use of artificial intelligence within either augmented reality, virtual reality, extended reality, mixed reality, the metaverse, or a combination of them in educational settings. Hence, documents that only referred to one of these technologies or that only mentioned the specific keywords but did not focus on them or their use in educational or training contexts were regarded as out of scope. Additionally, all documents that explored the combination of these technologies from a theoretical or experimental perspective in education were regarded as relevant. After processing the full text of the documents, 1741 documents were removed as they did not satisfy the inclusion criteria. As a result, the document collection examined and analyzed in this study consisted of 201 documents that were relevant to the topic. As previously mentioned, the use of abbreviations in the query resulted in a high number of documents being out of scope but simultaneously, ensured that all related documents would be identified. Moreover, it should be mentioned that although the vast majority of documents were duplicates between the two databases used, in total, most relevant documents were found in Web of Science while most of the irrelevant to the topic documents were reported from Scopus. This fact justified the difference in the number of articles initially retrieved.

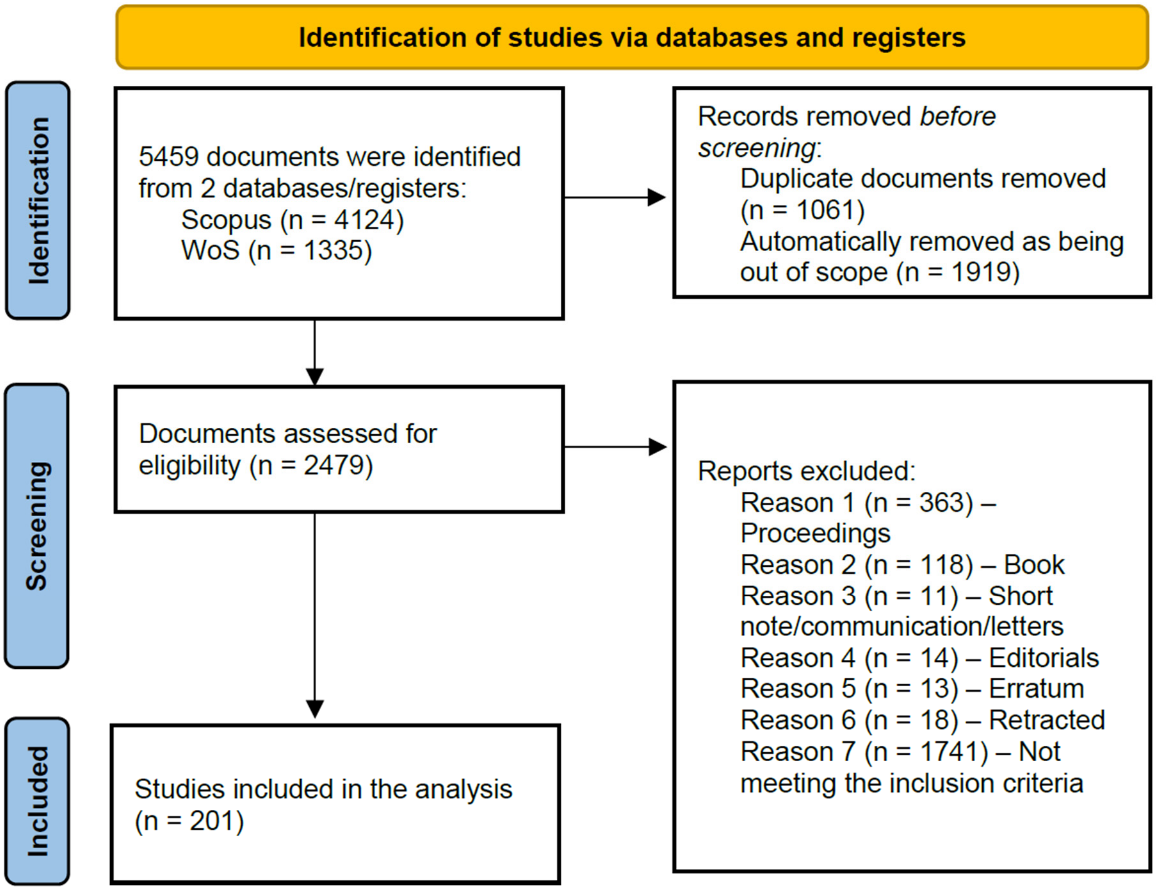

Figure 1. PRISMA flowchart.

3. Result Analysis

The document collection created was explored from various dimensions using different approaches to present the current state of the art regarding the combination of artificial intelligence with augmented reality and virtual reality technologies in education. Initially, the details of the document collection are presented. The publication frequency and the annual citation distribution are showcased. This study also looks into the authors' affiliation and countries and focuses on identifying the collaboration among the different countries. The relevant documents that have received the largest number of citations are also identified. Using keywords plus and author's keywords, the trends of the topic, its thematic map, and its thematic evolution are also examined. To identify more topics, the documents were clustered using both Bibliometrix and VOSviewer to carry out a keywords-based co-occurrence analysis. To further examine the topics, LDA [71] was used to carry out a topic modeling analysis of the document collection regarding the use of artificial intelligence and extended reality technologies in education.

3.1. Document Collection

The details of the complete document collection, which consists of 201 documents that were published during 2015–2024, are presented in Table 1. Most of the documents were published as conference/proceedings papers (42.8%), closely followed by journal articles (42.3%). To a lesser extent, the documents were published as book chapters (10.9%) or as review articles (4.0%) as indicated by the two databases. The documents were created and published by 642 authors. Each document had an average of 3.65 co-authors and the average citations per document was 13.82. In total, 32 authors contributed to the creation of 32 single-authored documents. It is worth highlighting that the average age of the documents is 1.63 and the annual growth rate demonstrates a significant positive rate of 60.58%. This fact highlights the importance and recency of the topic.

Table 1. Information regarding the document collection.

Description	Results	Description	Results
Main information about data		**Document types**	
Timespan	2015:2024	Article	85
Sources (journals, books, etc.)	142	Book chapter	22
Documents	201	Conference/Proceedings paper	86
Annual growth rate %	60.58	review	8
Document average age	1.63	**Authors**	
Average citations per document	13.82	Authors	642
		Authors of single-authored documents	32
Document contents		**Authors collaboration**	
Keywords plus (ID)	1293	Single-authored documents	32
Author's keywords (DE)	532	Co-authors per documents	3.65
		International co-authorships %	10.45

3.2. Publication Frequency and Citations

The significance of the topic and its high and positive annual growth rate (60.58%) become more evident when considering the distribution of the published documents from 2015 to 2024 (Figure 2). The majority of the documents were published in the last 3 years with the year 2024 having the most published documents (n = 71), followed by 2023 (n = 45) and 2022 (n = 34). Based on the specific period explored, three main time periods can be defined: (i) 2015–2020 (12.44% of the total documents published) was the period in which the initial interest in the combination of artificial intelligence with augmented reality and virtual reality in education sparked; (ii) 2021–2023 (52.24% of the total documents published) was the period in which the topic started to materialize; and (iii) 2024 (35.32% of the total documents published) was the breakthrough year. The outcomes are in line with the advancements in the respective fields in the recent years. When considering the applicability of these technologies and their potential to enrich and transform the educational process, the interest in the topic is expected to continue increasing. Moreover, the annual citations received were also explored as can be seen in Table 2. Specifically, Table 2 presents the year in which the documents were published (Year), the mean total citations that they have received (MeanTCperDoc), the number of published documents in that specific year (N), the mean annual total citations they have received (MeanTCperYear), as well as the total number of years that the documents of that year were citable (CitableYears). Certainly, besides the quality and impact of the studies, the citable years are a significant factor to the number of citations they have received. As a result, more recent studies have received fewer total citations on average when compared to older studies that helped establish this field of study. Hence, it becomes evident that documents published in 2019 (MeanTCperDoc = 46.5) and 2018 (MeanTCperDoc = 40.4), which were citable for 6 and 7 years respectively, had the highest mean total citations per document with the exception of the year 2015 in which a single document [75] was published that received 200 citations based on the data of the two databases. However, as this field of study is rapidly advancing and considering the average document age (1.63 years), it is expected that these outcomes will change in the future.

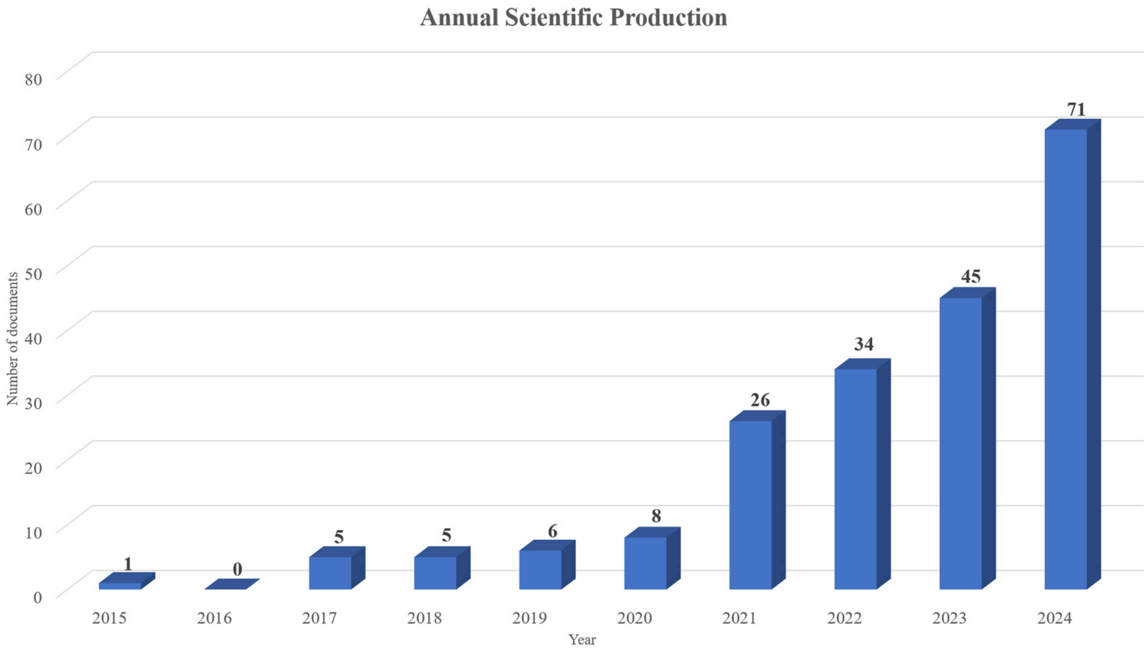

Figure 2. Number of documents published per year.

Table 2. Annual scientific production and citations.

Year	MeanTCperDoc	N	MeanTCperYear	CitableYears
2015	200	1	20	10
2017	8.2	5	1.02	8
2018	40.4	5	5.77	7
2019	46.5	6	7.75	6
2020	28.38	8	5.68	5
2021	22.12	26	5.53	4
2022	23.24	34	7.75	3
2023	8.27	45	4.14	2
2024	1.3	71	1.3	1

3.3. Sources

In total, the 201 documents that comprise the document collection examined in this study were published in 142 different sources, including journals, conference and proceedings, as well as edited book collections. Among the sources, the book series *Lecture Notes in Computer Science* (including subseries *Lecture Notes in Artificial Intelligence* and *Lecture Notes in Bioinformatics*) had the most published documents (n = 13) relevant to the topic. Moreover, three sources, namely, *Education and Information Technologies*, *Lecture Notes in Electrical Engineering*, and *Springer Series on Cultural Computing*, published four articles relevant to the topic. From the remaining sources, 13 sources published three relevant documents and 12 sources published two documents. A representation of the top four sources based on the number of relevant documents published that have published at least four documents is depicted in Table 3.

Table 3. Top sources based on the total number of relevant documents published.

Sources	Documents
Lecture Notes in Computer Science (including subseries *Lecture Notes in Artificial Intelligence* and *Lecture Notes in Bioinformatics*)	13
Education and Information Technologies	4
Lecture Notes in Electrical Engineering	4
Springer Series on Cultural Computing	4

Furthermore, the sources were also sorted based on their h-index and total citations received on the topic. The related outcomes are presented in Table 4 which depicts the h-index, g-index, m-index, total citations (TC), number of published documents (NP), and the publication start date (PY_start) of the sources. Based on the outcomes, *Computers and Education: Artificial Intelligence* (h-index = 3 and TC = 425), *Frontiers in Psychology* (h-index = 3 and TC = 62), and *Springer Series on Cultural Computing* (h-index = 3 and TC = 19) were the sources with the highest h-index (3). However, sources such as *International Journal of Artificial Intelligence in Education* (h-index = 2 and TC = 258) and *Lecture Notes in Computer Science* (including subseries *Lecture Notes in Artificial Intelligence* and *Lecture Notes in Bioinformatics*) (h-index = 2 and TC = 140) have also published impactful documents. The specific values that can be described as low, when compared to other bibliometric analysis studies that explore different topics, can be justified when we consider the average document age. Hence, given the fact that the topic is still in its infancy, the related outcomes are expected to change. However, the findings contribute by presenting the existing distribution of the documents among the various sources.

Table 4. Most impactful sources based on h-index.

Sources	h_Index	g_Index	m_Index	TC	NP	PY_Start
Computers and Education: Artificial Intelligence	3	3	0.75	425	3	2021
Frontiers in Psychology	3	3	0.75	62	3	2021
Springer Series on Cultural Computing	3	4	1.5	19	4	2023
International Journal of Artificial Intelligence in Education	2	3	0.2	258	3	2015
Lecture Notes in Computer Science (including subseries *Lecture Notes in Artificial Intelligence* and *Lecture Notes in Bioinformatics*)	2	11	0.25	140	13	2017
Computer Assisted Language Learning	2	2	0.667	91	2	2022
Nurse Education Today	2	2	0.5	68	2	2021
Education Sciences	2	3	0.5	58	3	2021
Applied Sciences (Switzerland)	2	3	0.5	48	3	2021
Mobile Information Systems	2	3	0.5	37	3	2021

Furthermore, Bradford's law was used to better comprehend the sources' impact and quality [76]. Specifically, three clusters were defined, namely, Cluster 1, Cluster 2, and Cluster 3, with Cluster 1 having the most impactful sources. Cluster 1 consists of 19 sources (13.4%) in which 68 documents (33.83%) were published, Cluster 2 comprises 57 sources (40.1%) in which 67 documents (33.33%) were published, and Cluster 3 has 66 sources (46.5%) in which 66 documents (32.84%) were published. Table 5 presents the top sources of Cluster 1 based on Bradford's law. Particularly, it presents the source name (Source), its rank (Rank), the number of documents published (Freq.), the cumulative frequency of published documents (CumFreq.), and the cluster (Cluster). Based on the outcomes, the top sources were *Lecture Notes in Computer Science* (including subseries *Lecture Notes in Artificial Intelligence* and *Lecture Notes in Bioinformatics*) (rank = 1 and freq. = 13), *Education and Information Technologies* (rank = 2 and freq. = 4), *Lecture Notes in Electrical Engineering* (rank = 3 and freq. = 4), *Springer Series on Cultural Computing* (rank = 4 and freq. = 4), *ACM International Conference Proceeding Series (ICPS)* (rank = 5 and freq. = 3), *Applied Sciences* (Switzerland) (rank = 6 and freq. = 3), *Cognitive Technologies* (rank = 7 and freq. = 3), *Computers and Education: Artificial Intelligence* (rank = 8 and freq. = 3), *Education Sciences* (rank = 9 and freq. = 3), and *Electronics* (Switzerland) (rank = 10 and freq. = 3).

Table 5. Most impactful sources based on Bradford's law.

Source	Rank	Freq.	CumFreq.	Cluster
Lecture Notes in Computer Science (including subseries *Lecture Notes in Artificial Intelligence* and *Lecture Notes in Bioinformatics*)	1	13	13	Cluster 1
Education and Information Technologies	2	4	17	Cluster 1
Lecture Notes in Electrical Engineering	3	4	21	Cluster 1
Springer Series on Cultural Computing	4	4	25	Cluster 1
ACM International Conference Proceeding Series (ICPS)	5	3	28	Cluster 1
Applied Sciences (Switzerland)	6	3	31	Cluster 1
Cognitive Technologies	7	3	34	Cluster 1
Computers and Education: Artificial Intelligence	8	3	37	Cluster 1
Education Sciences	9	3	40	Cluster 1
Electronics (Switzerland)	10	3	43	Cluster 1

3.4. Authors

Lotka's law was used to examine the number of authors that have contributed a set number of documents to the document collection included in this study. Based on the results presented in Table 6, it is evident that the vast majority of authors have contributed to a single study (89.7%). A total of 7.3% of authors have contributed to two documents and 13 authors (2.1%) have contributed to three studies. Finally, a total of six authors (0.9%) have contributed to four documents.

Table 6. Lotka's law analysis.

Documents Written	N. of Authors	Proportion of Authors
1	576	0.897
2	47	0.073
3	13	0.02
4	6	0.009

3.5. Affiliations

For a better understanding of the affiliations that have contributed the most in the creation and publication of documents relevant to the topic, the author affiliations were examined. Specifically, the affiliations of all authors involved in a document were taken into account. Hence, the total number of documents published by the authors of a specific country might be lower than the summation of the contribution from different affiliations of the same country. Hence, to examine the countries that have contributed the most, a separate analysis was carried out.

Among the different affiliations contained within the document collection, the top 10 affiliations, based on the number of contributions to documents, had contributed to at least four documents. Specifically, authors from McGill University, Canada (n = 11) and University of Essex, United Kingdom (n = 7) have contributed to the most documents.

Three affiliations, namely Texas A&M University, United States, University of Córdoba, Spain, and the University of Sydney, Australia, had authors who contributed to six documents. Two affiliations, namely AGH University of Science and Technology, Poland and Sungkyunkwan University, South Korea, had authors who contributed to five documents. Three affiliations, namely Delft University of Technology, Netherlands, National Chung Cheng University, Taiwan, and University of West Attica, Greece, had authors who contributed to four documents.

3.6. Countries

To examine the countries that have contributed the most to the creation of the document collection, the corresponding author's or the first author's country was taken into account. Specifically, the corresponding author's country was used and only if there was no corresponding author clearly defined, the first author's country was used. As a result, a total of 40 countries were identified.

In Table 7, the top 10 countries that have contributed the most documents on the topic are presented. Each of the remaining countries contributed three or fewer documents. Specifically, Table 7 presents the name of the country (Country), the number of documents (Documents), the intra-country collaboration (SCP), the inter-country collaboration (MCP), the frequency (Freq.), and the inter-country collaboration ratio (MCP_Ration). China (n = 61), the United States (n = 28), India (n = 13), and the United Kingdom (n = 8) were the countries that contributed the most documents. Additionally, China had the most intra-country (n = 57) and inter-country (n = 4) collaborations among all 40 countries.

Table 7. Country publication details.

Country	Documents	SCP	MCP	Freq.	MCP_Ratio
China	61	57	4	0.303	0.066
United States	28	26	2	0.139	0.071
India	13	12	1	0.065	0.077
United Kingdom	8	8	0	0.04	0
Canada	7	5	2	0.035	0.286
Italy	7	5	2	0.035	0.286
Australia	6	6	0	0.03	0
South Korea	6	6	0	0.03	0
Greece	5	5	0	0.025	0
Germany	4	4	0	0.02	0
Indonesia	4	4	0	0.02	0
Spain	4	2	2	0.02	0

Furthermore, Table 8 presents the countries that received the most citations based on the availability of the cited references information provided by the two databases used. China received the most citations (n = 954), followed by the United States (n = 527) and Canada (n = 453). Additionally, Canada has the highest number of average citations per document (64.7). Finally, the document contributed by authors in New Zealand [75] received a total of 200 references based on the information of the two databases which highlight its impact and significance.

Given that only 15.9% of the documents were single-authored, that the documents had on average 3.65 co-authors, and that the international co-authorship rate was 10.45%, it was deemed important to explore the collaboration among the different countries. As can be seen in Figure 3, in total, five clusters emerged. These clusters highlight the countries whose authors are actively involved in joint efforts to further advance this field of study and also present the countries that have been involved in more international collaborations. Of the countries presented, China, followed by the United States, had the most collaborations with other countries, having both direct and indirect connections.

Table 8. Countries that received the most citations.

Country	TC	Average Document Citations
China	954	15.6
United States	527	18.8
Canada	453	64.7
New Zealand	200	200
Australia	144	24
India	103	7.9
Italy	67	9.6
South Korea	62	10.3
Serbia	40	20
Spain	39	9.8

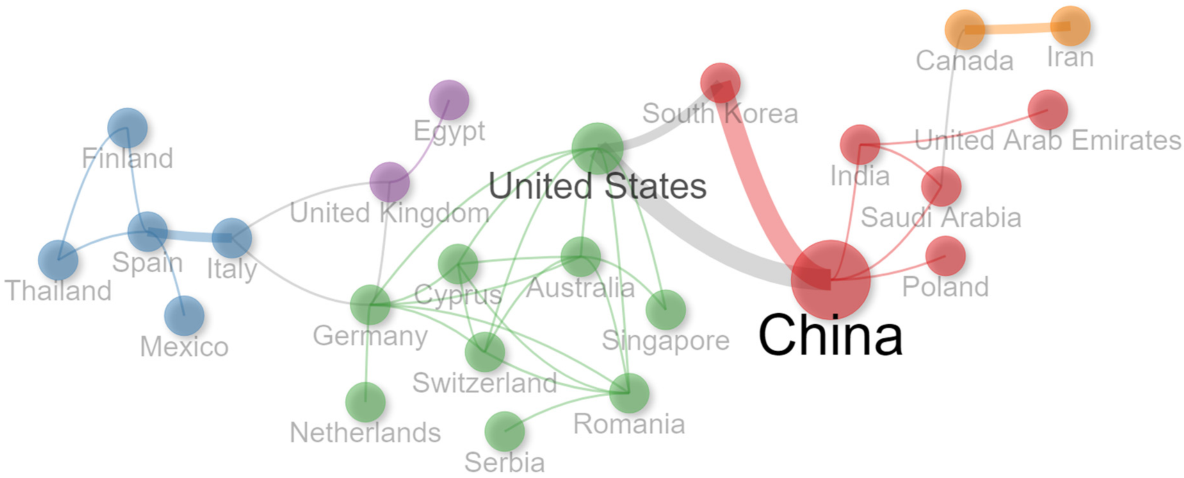

Figure 3. Country collaboration network.

3.7. Document Analysis

To further explore the related documents, the total number of citations they have received was considered. Additionally, using the keywords specified within the documents, the thematic evolution of the topic, the thematic map of the topic, and the main trends of the topic were explored. Specifically, Table 9 presents the documents that have received the most citations within the document collection.

Table 9. Documents with the highest number of citations.

Document	DOI	Total Citations	Total Citations Per Year	Normalized Total Citations
[77]	10.1016/j.caeai.2022.100082	372	124	16.01
[75]	10.1007/s40593-014-0032-x	200	20	1
[78]	10.1016/j.jsurg.2019.05.015	154	25.67	3.31
[79]	10.1371/journal.pone.0229596	150	30	5.29
[80]	10.1007/978-3-319-93843-1_12	135	19.29	3.34
[81]	10.1016/j.imr.2022.100917	89	44.5	10.77
[82]	10.2106/JBJS.18.01197	82	13.67	1.76
[83]	10.1080/09588221.2021.1879162	67	22.33	2.88
[84]	10.1001/jamanetworkopen.2021.49008	65	21.67	2.8
[85]	10.1155/2021/2637439	61	15.25	2.76

The keywords reported by the two databases are categorized into keywords plus and author's keywords. Specifically, keywords plus refer to the keywords used to classify the documents within the databases while author's keywords refer to the keywords specified by the authors within the documents. Both types of keywords can adequately represent the document knowledge structure [86]. Hence, both types of keywords are used in this study.

The top 10 most frequently used keywords plus were "artificial intelligence", "virtual reality", "augmented reality", "education", "metaverse", "extended reality", "deep learning", "human-computer interaction", "chatbots", "immersive learning", and "intelligent tutoring systems". The top 10 most common author's keywords were "artificial intelligence", "virtual reality", "students", "e-learning", "augmented reality", "engineering education", "learning systems", "teaching", "computer-aided instruction", and "education". The frequency of the related keywords is presented in Figures 4 and 5 for the keywords plus and author's keywords respectively. According to the keywords, the ability of these technologies to provide immersive learning environments that tend to students' needs is highlighted. Moreover, their ability to personalize the educational process through the provision of intelligent tutoring systems, chatbots, and agents as well as interactive learning systems is evident. The importance of focusing on human-computer interaction and on providing effective computer-aided instruction emerged. Finally, their potentials to support both teachers and students is also presented through the identification of relevant keywords.

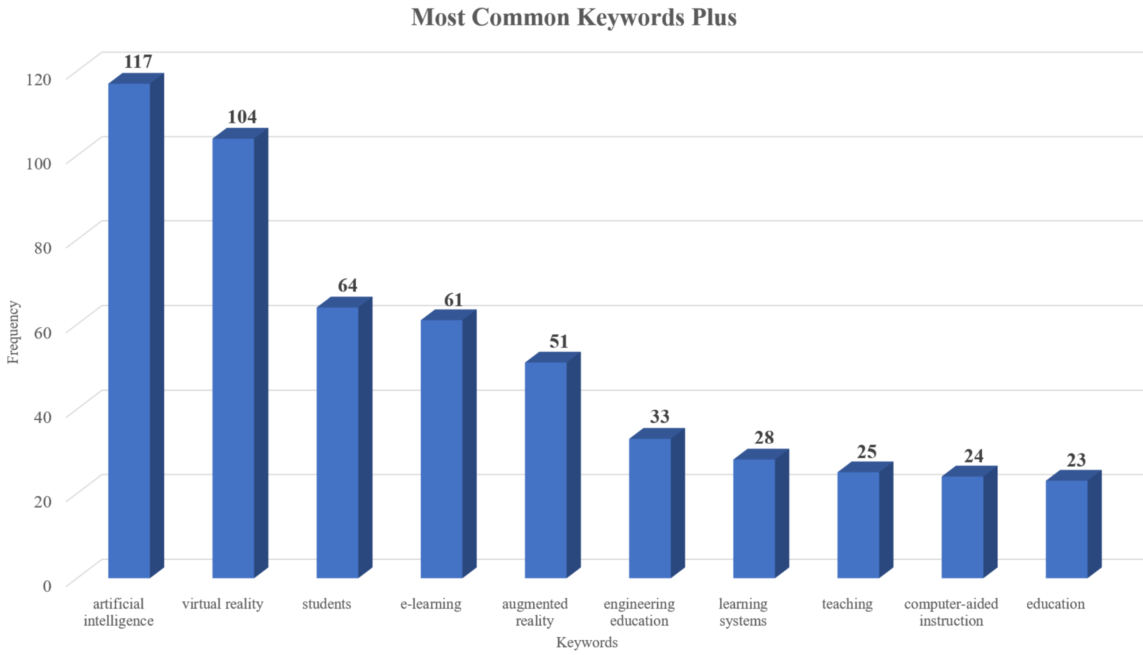

Figure 4. Most frequent keywords plus.

Besides the use of the Bibliometrix tool, VOSviewer was also used to explore the keyword co-occurrence network. The two networks are presented in Figures 6 and 7 respectively. For the networks generated via Bibliometrix (Figure 6), keywords plus were used, while for the network created via VOSviewer (Figure 7), author's keywords and keywords plus were used jointly. In the network created through Bibliometrix, a total of three clusters arose. The keywords of each cluster are as follows: (i) Green cluster: "virtual reality", "artificial intelligence", "students", "e-learning", "augmented reality", "engineering education", "learning systems", "teaching", "computer-aided instruction", "natural language processing", "education computing", "metaverse", "intelligent tutoring systems", "mixed reality", "learning", "deep learning", "extended reality", "curricula", "human-computer interaction", "learning experiences", "chatbots", "immersive learning", "immersive", "technology", "behavioral research", "speech recognition", "teachers", "artificial intelligence in education", "data handling", "language learning", "virtual assistants", "college students", "current", "learning environments"; (ii) Red cluster: "education", "machine learning", "medical education", "clinical competence", "medical", "simulation training", "nursing education", "procedures", "surgical training"; and (iii) Blue cluster: "virtual environments", "adversarial machine learning", "contrastive learning", "federated learning", "high education".

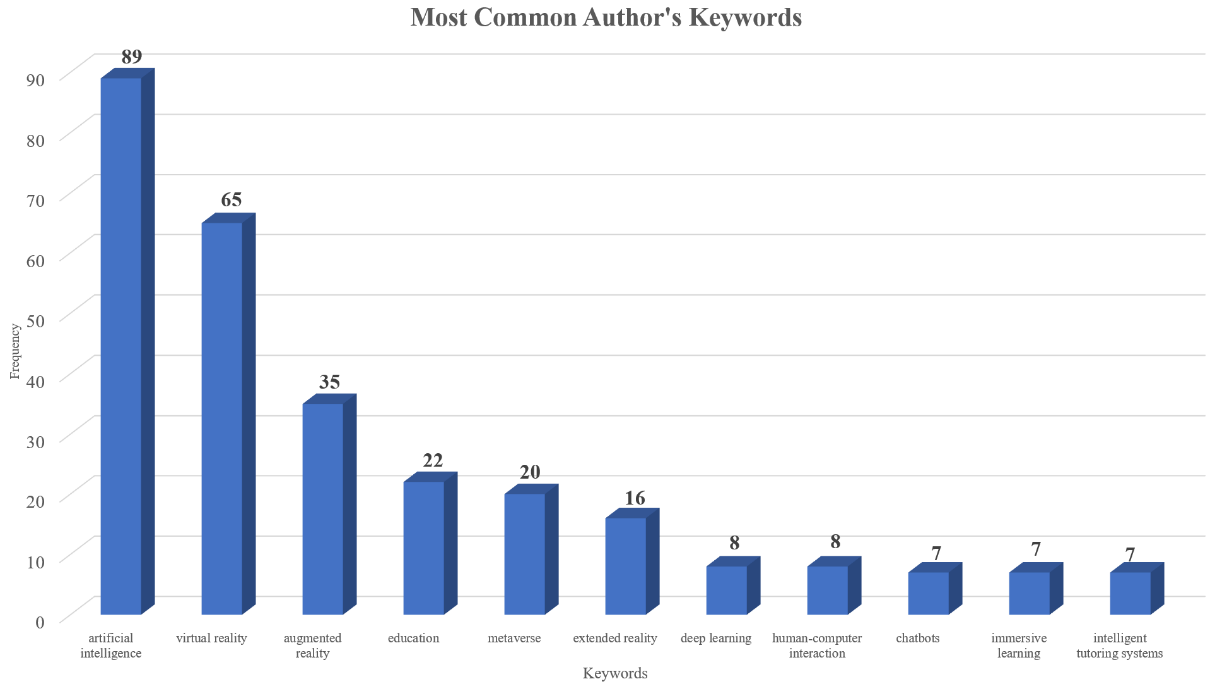

Figure 5. Most frequent author's keywords.

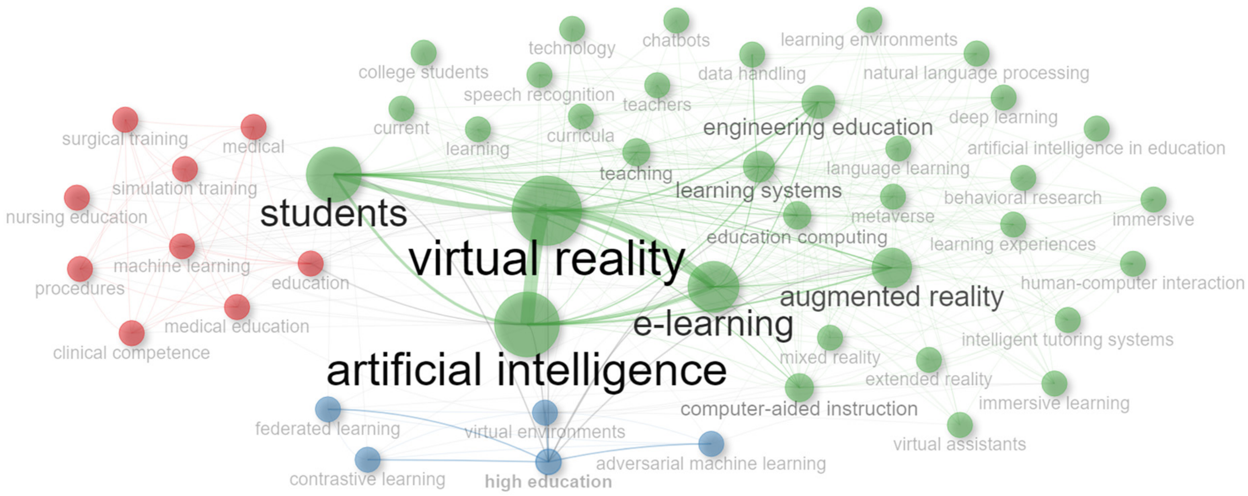

Figure 6. Keyword co-occurrence network—Bibliometrix.

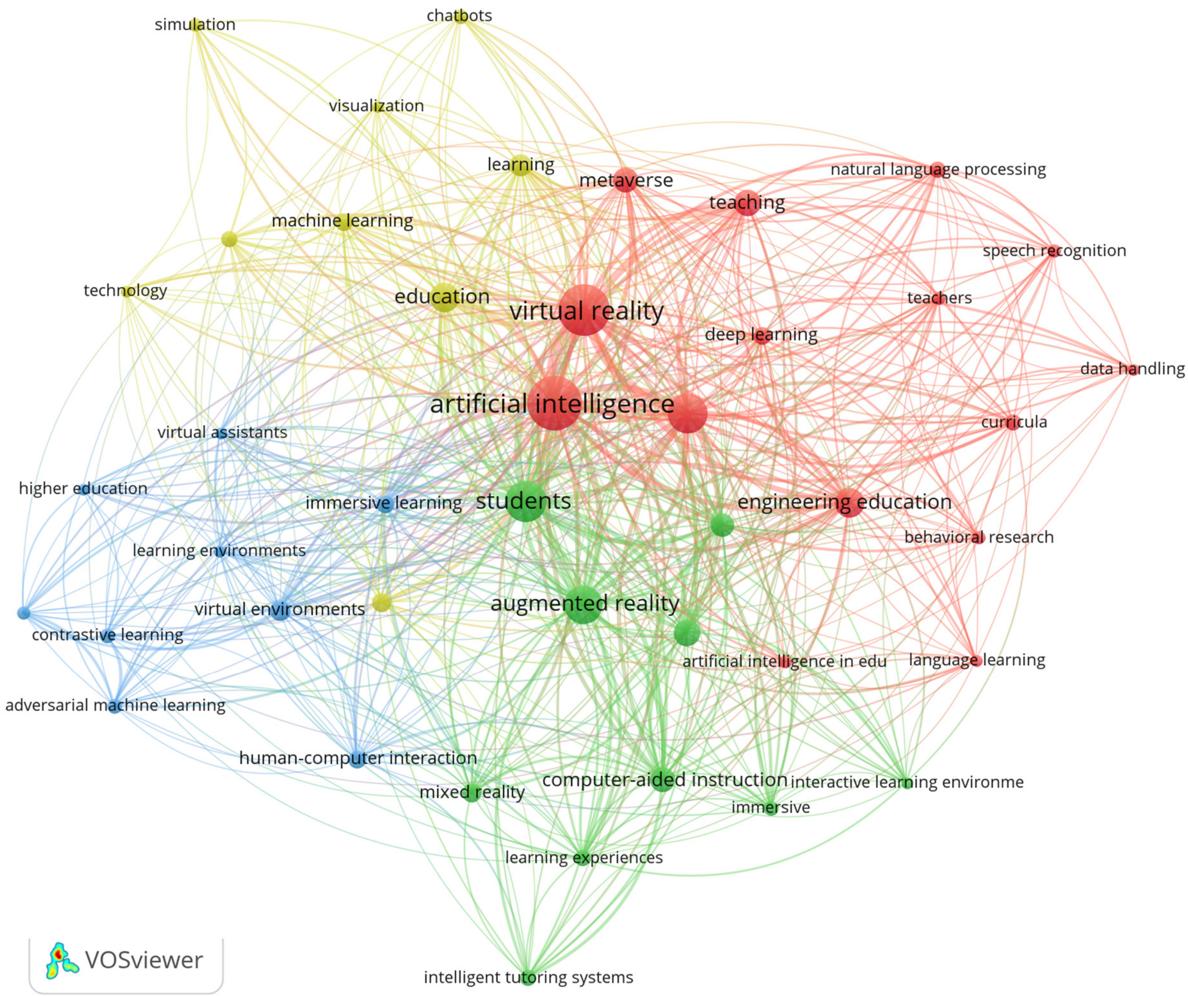

Figure 7. Keyword co-occurrence network—VOSviewer.

Moreover, the network generated through VOSviewer resulted in the creation of four clusters. The relevant to each cluster keywords are as follows: Cluster (1): "artificial intelligence", "artificial intelligence in education", "behavioral research", "curricula", "data handling", "deep learning", "e-learning", "engineering education", "language learning", "metaverse", "natural language processing", "speech recognition", "teachers", "teaching", "virtual reality"; Cluster (2): "augmented reality", "computer-aided instruction", "education computing", "immersive", "intelligent tutoring systems", "interactive learning environment", "learning experiences", "learning systems", "mixed reality", "students"; Cluster (3): "adversarial machine learning", "contrastive learning", "federated learning", "higher education", "human-computer interaction", "immersive learning", "learning environments", "virtual assistants", "virtual environments"; and Cluster (4): "chatbots", "education", "extended reality", "learning", "machine learning", "medical education", "simulation", "technology", "visualization". The applicability and multidimensional role of combining artificial intelligence with augmented reality and virtual reality technologies in educational settings is evident from the keywords and clusters.

Furthermore, through the use of VOSviewer, the total link strength among the keywords and their connections were explored. The related keywords were further processed and both keywords plus and author's keywords were used. Nonetheless, to avoid any bias, if a keyword existed in both keyword sets, it counted only once. Table 10 presents the top 10 keywords based on their total link strength. Artificial intelligence (occurrence = 111 and total link strength = 458), virtual reality (occurrence = 100 and total link strength = 444), and students (occurrence = 64 and total link strength = 361) were the keywords with the highest total link strength. Augmented reality also had a relatively high total link strength; however, it was less than that of the virtual reality keyword. This fact highlights the closer relation between artificial intelligence and virtual reality and that the research into the field of virtual reality has been more extensively examined.

Table 10. Total link strength of the keyword co-occurrence network—VOSviewer.

Keywords	Occurrences	Total Link Strength
artificial intelligence	111	458
virtual reality	100	444
students	64	361
e-learning	60	318
augmented reality	54	236
engineering education	33	178
learning systems	28	172
education	32	163
computer-aided instruction	24	150

Using Bibliometrix, the evolution of the topic throughout the years was also examined. Given the 10-year time period examined in this study (2015–2024), a total of three distinct time periods were set, as can be seen in (Figure 8). To examine the thematic evolution, the document keywords were used. Hence, each time period was associated with a set of keywords. Specifically, the following themes emerged over the years: (i) 2015–2018 period: virtual reality, computer-aided instruction; (ii) 2019–2021 period: artificial intelligence, extended reality, deep learning, education, learning efficiency, learning systems; and (iii) 2022–2024 period: artificial intelligence, metaverse, education, virtual environments, and tutoring systems. Based on the outcomes, the close relationship between extended reality technologies and artificial intelligence becomes evident. However, the field of virtual reality is more widely being examined in combination with artificial intelligence than with that of augmented reality. Additionally, the initial focus on general computer-aided instruction has shifted to exploring how the combination of artificial intelligence and extended reality technologies can constitute effective learning systems that can improve learning efficiency and support the educational process through the use of advanced technologies and approaches, such as deep learning techniques. In recent years, more emphasis has been placed on the metaverse and on creating effective virtual environments as well as personalized tutoring systems that can enrich the educational process.

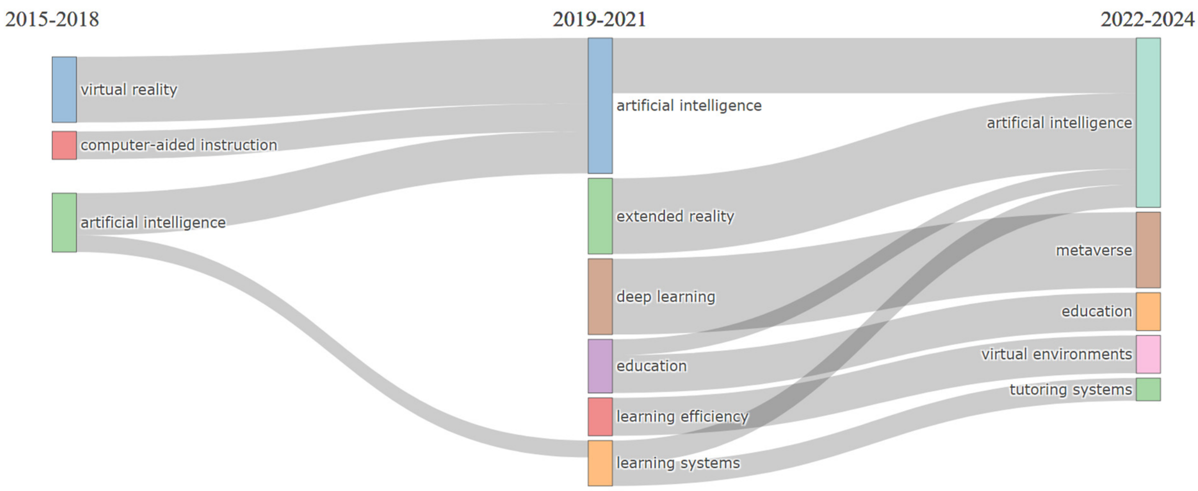

Figure 8. Thematic evolution of the topic.

The trend topics that emerged over the period of 2015–2024 were also explored. The related outcomes are presented in Figure 9 for the keywords plus and in Figure 10 for the author's keywords. Based on the author's keywords, the emphasis on intelligent tutoring systems is evident. Additionally, the focus on augmented reality and virtual reality started to appear more intensely in 2021 while on the metaverse in 2023. Creating immersive learning and personalized learning environments using extended reality and artificial intelligence technologies to support teaching and learning has been the main focus in the last years. According to the outcomes of the keywords plus analysis, the initial emphasis was placed in the field of medical and healthcare education. Gradually, the focus shifted to other fields and subjects as well. The interest in using new technologies and approaches to support teaching and learning by offering, intelligent tutoring systems, computer-aided instructions, and interactive learning systems was evident. Recently, emphasis has been put on different machine learning and deep learning techniques to provide personalized and immersive learning experiences in virtual environments while also capitalizing on virtual assistants and virtual avatars.

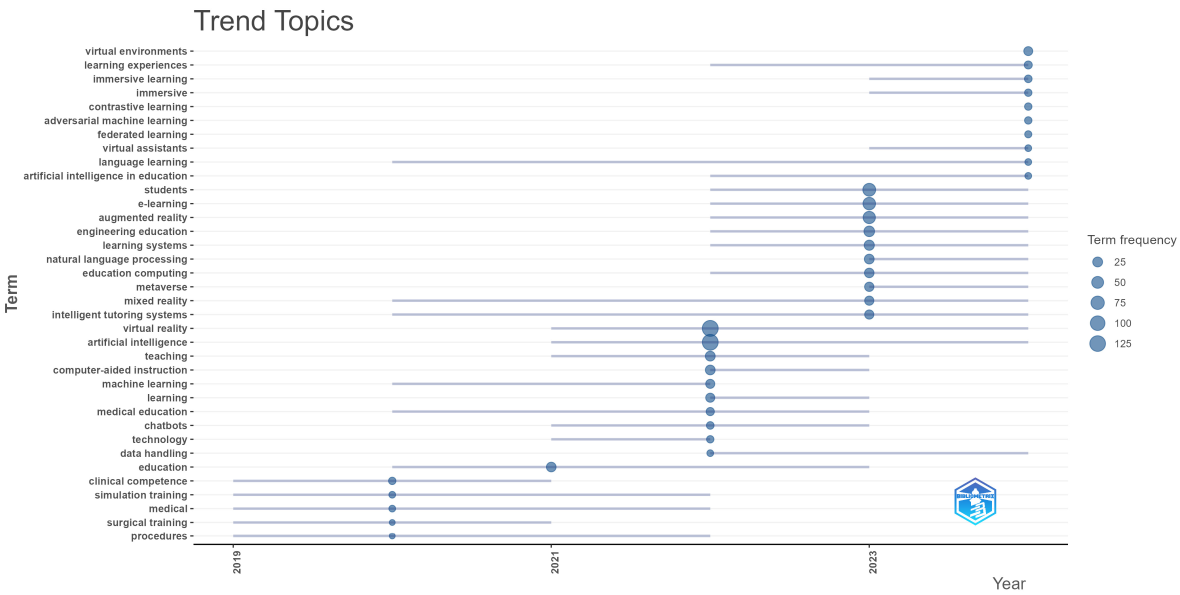

Figure 9. Trend topics based on keywords plus.

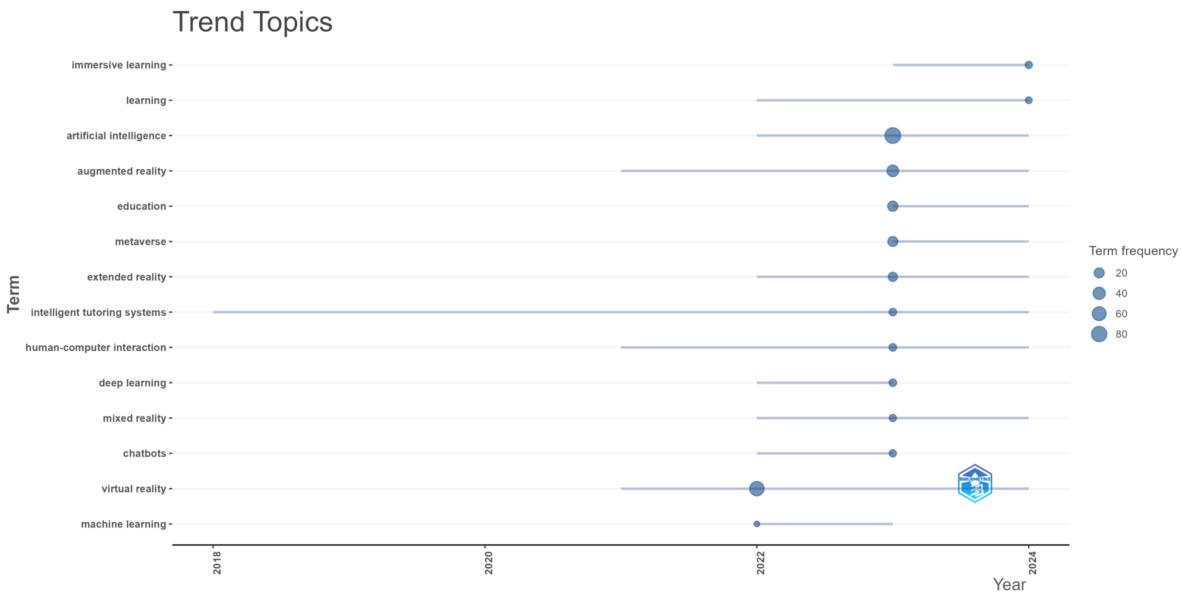

Figure 10. Trend topics based on author's keywords.

Keywords were also used to cluster the documents through the use of the clustering by coupling method using keywords plus as the coupling measurement and documents as the analysis unit. The related outcomes are presented in Figure 11, based on which six clusters arose. The first cluster (brown) was related to the keywords "artificial intelligence", "virtual reality", "education", "e-learning", and "clinical competence" while the second cluster (green) was related to the keywords "virtual reality", "artificial intelligence", "e-learning", "students", and "natural language processing". Both clusters highlight the close relation between artificial intelligence and virtual reality in educational settings. The third cluster (red) was associated with the keywords "artificial intelligence", "augmented reality", "mixed reality", "engineering education", and "learning systems", revealing the focus on combining augmented reality with artificial intelligence to create learning systems that promote learning in mixed reality environments, particularly in STEM-related fields. The fourth cluster (orange) was associated with the keywords "students", "augmented reality", "e-learning", "virtual reality", and "computer-aided instruction" while the fifth cluster (purple) was related to the keywords "adversarial machine learning", "contrastive learning", "federated learning", "students", and "virtual environments". These clusters present the use of new techniques and approaches to enrich learning in virtual environments and to provide students with personalized computer-aided instruction. The sixth cluster (blue) was related to the keywords "augmented reality", "intelligent tutoring systems", "students", "computer-aided instruction", and "education computing" which highlights the emphasis on using intelligent tutoring systems within augmented reality environments to provide students with personalized computer-aided instruction.

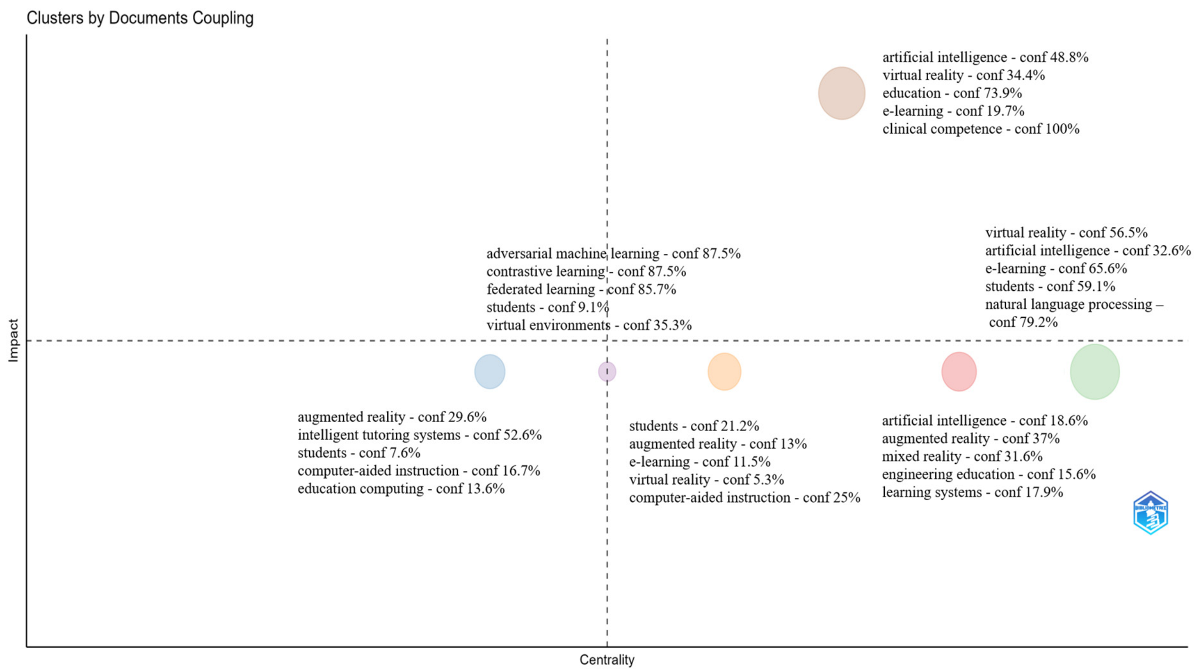

Figure 11. Document clusters.

Furthermore, using Bibliometrix, the thematic map of the topic, focusing on identifying the motor, basic, niche, and emerging or declining themes, was created. In total, 11 themes emerged. Motor themes (three clusters) were related to (i), "medical", "procedures", "surgical training", and "simulation"; (ii) "intelligent tutoring systems", "interactive learning environment", "user interfaces", and "virtual reality training"; and (iii) "nursing", "nursing education", and "nursing students". Basic themes (four clusters) were associated with (i) "teaching", "metaverse", "curricula", and "behavioral research"; (ii) "students", "e-learning", "augmented reality", and "engineering education"; (iii) "education", "machine learning", and "medical education"; and (iv) "virtual reality", "artificial intelligence", "learning", and "extended reality". Niche themes (two clusters) were related to (i) "instructional design", "intelligent robots", and "intelligent systems" and (ii) "artificial intelligence algorithms", "development prospects", and "efficiency". Emerging or declining themes (two clusters) were associated with (i) "adaptive learning", "design considerations", "innovation", and "learning technologies" and (ii) "college students", "motivation", and "sustainable development". Figure 12 depicts the related information.

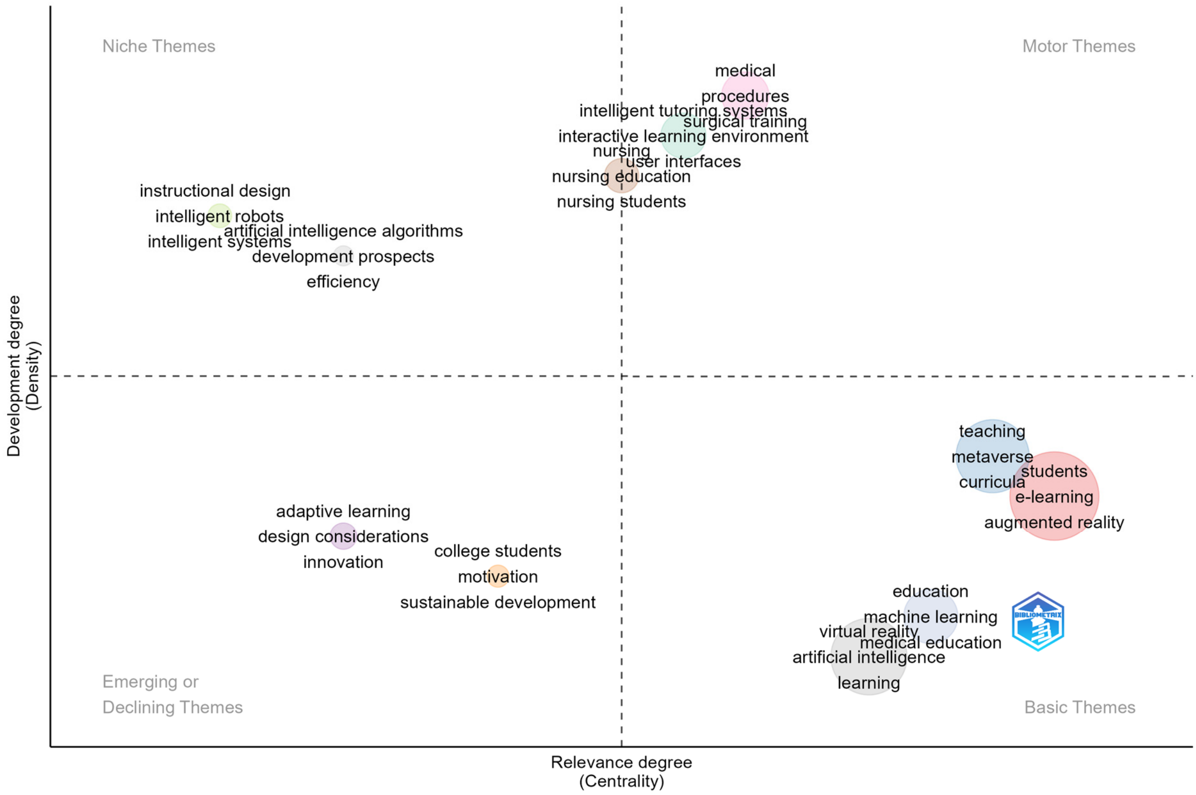

Figure 12. Thematic map of the topic.

In addition to the results of Bibliometrix and VOSviewer, which focused on keywords, topic modeling was also used through LDA. Specifically, LDA is used on discrete datasets to represent each item as a combination of topics from a finite set and constitutes a probabilistic Bayesian model with a three-level hierarchical structure [71]. The results of the topic modeling analysis are based on the bi-grams contained within the title and abstract of the documents and are presented in Table 11. The main keywords associated with the topic (e.g., artificial intelligence, augmented reality, virtual reality, extended reality, and mixed reality) are not reported to present more representative outcomes. In total, three topics arose from the topic modeling analysis. These topics were related to the wide applicability of artificial intelligence, augmented reality, and virtual reality in education. Specifically, the first topic is related to their role in higher education, to the focus on students' learning and improving their learning outcomes, as well as the design and adoption of appropriate teaching practices and methods. The second topic is related to the use of intelligent tutoring systems and virtual assistants and avatars within learning environments to promote and increase learning outcomes. The third topic is related to the wide range of educational subjects into which these technologies can be effectively integrated and to the emphasis on interactive and immersive learning experiences and environments. These outcomes are in line with those identified by the two tools used and provide additional details for each topic.

Table 11. LDA topic modeling.

No.	Topic	Bi-Grams
1	Higher education–Teaching practices and methods—Learning outcomes	higher education (8.856), application technology (6.281), learning outcomes (4.579), deep learning (4.143), machine learning (3.324), teaching method (3.054), teaching mode (3.042), student learning (2.999), learning technology (2.731).
2	Intelligent tutoring systems—Virtual assistants and avatars—Learning outcomes	intelligent tutoring (9.008), college students (4.921), educational environment (4.189), education research (3.814), virtual assistants (3.759), tutoring systems (3.743), students learning (3.512), improve learning (3.235), learning environments (3.005).
3	Interactive and immersive learning experiences—Educational subjects	learning experiences (6.909), language learning (6.818), nursing education (5.743), learning environment (5.729), real time (5.407), learning experience (5.299), interactive learning (4.817), engineering education (4.674), immersive learning (4.361), science education (4.329), computer science (3.339), medical education (3.240), emerging technologies (3.084).

4. Discussion

Both artificial intelligence and extended reality technologies can significantly impact teaching and learning activities; thus, transforming and enriching the educational domain. These outcomes can potentially be further amplified when these technologies are combined to yield intelligent, interactive, and immersive learning environments. However, despite the potential benefits that their use and the use of digital technologies in general can bring in education, it is important to consider the challenges associated with technology-enhanced learning in terms of the digital inclusion, digital exclusion, and the digital divide [87,88]. Specifically, the integration of more advanced technological applications into teaching and learning could create further inequalities between students who have access to them than those who do not [89,90].

To explore the advances of using extended reality technologies and artificial intelligence in education, the document collection focused on documents published in the last decade and their analysis looked into different dimensions and aspects of this collection. In total, 201 documents relevant to the integration of these technologies in educational settings comprised the document collection examined in this study. The PRISMA guidelines were adopted to ensure a valid, transparent, and reproducible study. The documents were retrieved from Scopus and Web of Science, which are highly regarded and widely used in systematic literature review and bibliometric analysis studies, and were utilized to search for documents relevant to the topic using a comprehensive query. The related documents were then processed and categorized. Using different tools and approaches, such as Bibliometrix, VOSviewer, and topic modeling through LDA, the documents contained within the specific document collection were analyzed.

The 201 documents contained in the document collection were published between 2015 and 2024. The documents had an average age of 1.63 years and a significantly high annual growth rate (60.58%). These outcomes highlight the importance and recency of the topic and indicate the use of artificial intelligence and extended reality in education as key technologies to shape up the future of the educational domain. The documents were published in 142 different sources with most documents having been published as conference/proceedings papers (42.8%), closely followed by journal articles (42.3%). The documents were written by 642 authors from 40 different countries and had an average of 3.65% co-authors. As the topic is still in its infancy, the international co-authorship rate (10.45%) reveals the multidisciplinary nature of the topic and it being widely examined by researchers of different expertise across countries and continents. Nonetheless, a relatively high number of single-authored studies (15.92%), in comparison to other topics, was also observed. Given the document publication period of 2015–2024, the time period was divided into three periods. Specifically, 2015–2020 was the period when interest in this topic sparked, 2021–2023 was the period when the topic began to materialize, and 2024 was the breakthrough year. Additionally, most documents were published in 2024 (35.32%), followed by those published in 2023 (22.39%) and 2022 (16.92%). Among the 201 documents, those that were published in 2019 and 2018 had the highest mean total citations per document. However, given the annual growth rate and the average age of the documents, it is expected that the outcomes regarding the publication year of the most impactful documents is subject to change. Moreover, using the number of published documents, the total citations, and the h-index on the topic, the sources in which the documents were published were also explored. Bradford's law was also used to cluster the sources based on their relevancy to the topic. Through the use of Lotka's law, it became evident that a significant majority of authors have contributed to a single study (89.7%); however, as the field advances, it is expected that these outcomes will change. Additionally, the countries and affiliations whose authors have contributed the most documents on the topic and received the most citations were also examined. Specifically, China, the United States, India, and the United Kingdom contributed the most documents while China, the United States, and Canada received the most citations. China also had the most intra-country and inter-country collaborations among all countries. Finally, five clusters of close collaborations among authors from different countries emerged when examining the international collaborations. These results highlight the interdisciplinary nature of the topic as well as the global interest in the integration and use of artificial intelligence, augmented reality, and virtual reality in education.

To identify topics and areas of interest, both author's keywords and keywords plus were used. When examining the frequency at which the keywords were used, the ability to offer immersive and interactive learning experiences through the convergence of artificial intelligence and extended reality technologies emerged. Additionally, the importance of human-computer interaction, machine learning and deep learning, computer vision, and natural language processing arose. The ability to support both teachers and students and offer computer-aided instruction was also evident. The potential to create intelligent tutoring systems and virtual assistants was highlighted as well. Although these technologies can be integrated into a plethora of learning subjects, most emphasis is being put on their use in engineering and STEM education. The multidimensional nature and wide applicability of these technologies were also revealed through the keyword co-occurrence network analysis in both Bibliometrix and VOSviewer. Specifically, using Bibliometrix, the documents were categorized into three clusters while using VOSviewer four clusters emerged. In both cases, the outcomes were similar and revealed their ability to be used as effective learning systems that can be integrated into the curricula, offer computer-aided instruction, provide interactive and immersive experiences, and support both teachers and students. Additionally, through intelligent agents, chatbots, intelligent tutoring systems, and virtual assistants, intelligent tutors that are characterized by high levels of realism, personalization, interactivity, as well as cognitive, emotional, and social skills can be created when combining artificial intelligence with augmented reality and virtual reality technologies. Among the clusters, the emphasis on higher education, engineering and medical education, as well as on hands-on learning experiences through immersive simulations is evident. The vital role of machine learning and deep learning methods for speech and motion recognition, computer vision, eye tracking, natural language processing, as well as content personalization and recommendation was highlighted. These outcomes were further highlighted and validated within the document clustering. When examining the link strength among the keywords, artificial intelligence, virtual reality, and students had the highest total link strength. This fact highlights the emphasis that is being put on students and student-centered learning environments as well as the focus on using artificial intelligence within virtual reality environments. Although augmented reality also had a relatively high total link strength, virtual reality being the prominent area of focus was evident throughout the analysis. This fact is in line with the keyword frequency analysis and further validates the outcomes of other related studies [91] which have indicated that the field of virtual reality has been more extensively examined than that of augmented reality on which more focus is being given in recent years. It should also be noted that of the different types of artificial intelligence, emphasis is being placed on the use of machine learning and deep learning approaches. Additionally, the topic modeling outcomes revealed the following three main topics: (i) the role of extended reality technologies and artificial intelligence in higher education and the focus on improving students' learning and outcomes as well as the design and adoption of appropriate teaching practices and methods; (ii) the use of intelligent tutoring systems and virtual assistants and avatars within learning environments to promote and increase learning outcomes; and (iii) their use in different educational subjects while emphasizing interactive and immersive learning.

Furthermore, the transition from virtual reality and augmented reality educational interventions to artificial intelligence-enabled extended reality systems and virtual environments was also highlighted in the thematic evolution of the topic in which three periods were defined. Based on the related keywords, emphasis is put on students' academic achievements, intelligent tutoring systems, personalized learning, immersive virtual environments, and learning efficiency. Besides augmented reality and virtual reality technologies, there has been increasing interest in the use of the metaverse in education. When examining the trend topics, the transition from the initial focus on medical and healthcare education to other fields and subjects was observed. Additionally, the gradual enrichment of extended reality experiences and environments with artificial intelligence and the emphasis on offering intelligent tutoring systems in the form of virtual avatars that provide personalized and immersive learning was highlighted. However, it should be noted that the advancements in this field are dependent on industrial productions and these changes are tightly coupled to other factors. For example, the wider use of generative artificial intelligence through tools such as Bard, ChatGPT, Gemini, etc., the hardware improvement in terms of processing capabilities, and the advancement of head-mounted devices (e.g., HoloLens, Meta Quest, etc.) may also influence the increased interest in the field and the increase in the number of published documents.

Moreover, the studies presented in Table 9, which identified the documents that have received the most citations within the document collection based on the data reported by the two databases, are discussed. In their study, Hwang and Chien [77] examined the research issues associated with the adoption of the metaverse in education from an artificial intelligence-based perspective. Their study also focused on presenting the potential applications of the metaverse in educational settings. Emphasis was also placed on the role of artificial intelligence in the metaverse. Ethical issues, the need for specialized hardware and software, and the lack of relevant technological support arose as the main challenges. Finally, the study highlights the need for future studies to focus on curriculum and learning design within the metaverse. Westerfield et al. [75] focused on combining augmented reality with intelligent tutoring system to aid in the learning and training of manual assembly tasks. Their study aimed at offering a more effective learning experience to assemble a motherboard. Based on their outcomes, students who learned through the intelligent augmented reality system completed the tasks faster and achieved better performance than those who learned through the basic augmented reality system. Hence, they highlighted the potential of intelligent augmented reality tutors as a means to improve learning.

Winkler-Schwartz et al. [78] put emphasis on improving and assessing surgical expertise in the context of medical education using machine learning and a virtual reality simulation. Aiming at effectively evaluating the performance on virtual reality simulators regarding surgical expertise, they created and presented the Machine Learning to Assess Surgical Expertise (MLASE) checklist. They examined published articles that used these technologies and found out that articles published in computer science journals had a more in-depth description of the study design and weaker discussion quality while articles that were published in medical journals were the exact opposite. Hence, this checklist aims to provide common ground for future studies to use to assess the effectiveness of their systems and applications. Mirchi et al. [79] explored the creation of a virtual operative assistant using virtual reality and explainable artificial intelligence tools. Specifically, they focused on simulation-based training in surgery and medicine in the context of medical education. Their virtual operative assistant was capable of effectively classifying the users into different categories based on their skills and performance and provided them with immediate visual feedback. Their study also highlighted the potential benefits that the use of artificial intelligence and virtual reality can have in education as well as the merits that can be yielded when combining instructor inputs, objective feedback, and expertise classification.

Focusing on artificial intelligence-enhanced classrooms, Holstein et al. [80] examined the influence of using a mixed-reality teacher awareness tool on students' learning in K-12 education. Their results revealed that through the use of intelligent tutoring systems and real-time analytics, it is possible to reduce the disparity in learning outcomes among students with different levels of prior ability. Finally, the study comments upon the potential benefits that can be yielded when integrating machine and human intelligence in classrooms to support students' learning. Divekar et al. [83] focused on the design and evaluation aspects of foreign language learning using extended reality technologies and artificial intelligence. Based on the outcomes, students had a positive learning experience and statistically significant differences were observed in knowledge acquisition and retention. Hence, the study highlighted that the combination of extended reality technologies with artificial intelligence can result in effective and naturalistic conversational interaction that can improve learning outcomes in the context of foreign language learning. Ma [84] also focused on exploring the combination of artificial intelligence, machine learning, and virtual reality as an immersive context teaching method for foreign language learning in higher education. The study revealed the immersive and interactive nature of virtual reality learning environments. Additionally, it highlighted the positive impact that this combination can have on students' learning outcomes as students who learned through this approach performed better than those of the control group who adopted common traditional teaching methods. Finally, the study pointed out the benefits of combining virtual reality with constructivism theory to improve students' learning.

Ahuja et al. [81] put emphasis on the potential applications of the metaverse in medical education, in integrative health, and in artificial intelligence. Their study went over the related concepts and highlighted the role and benefits of the metaverse in each domain. Additionally, the combination of the metaverse with artificial intelligence, virtual reality, and augmented reality technologies was highly regarded due to its potential applications in the field of healthcare in the context of medical education. The study quoted that this combination could revolutionize and shift the paradigm of traditional medical education.

Bissonnette et al. [82] also focused on the use of virtual reality and artificial intelligence within medical education focusing on surgical training. Their study put emphasis on different algorithms and their ability to effectively perform classification tasks within virtual reality training scenarios. Their approach showed a high level of accuracy across twelve metrics when retrieving and analyzing real-time data from the virtual reality environment. Finally, the study highlighted the potential of artificial intelligence to support and enrich current educational paradigms and better prepare future professionals. Focusing on examining the influence of artificial intelligence tutoring on medical students' surgical skills, Fazlollahi et al. [84] carried out a study involving a virtual operative assistant. According to their findings, when compared to instructor-based teaching and to the control group, the group of students, who learnt through the virtual operative assistant within the virtual reality environment, showcased significantly improved outcomes in practice expertise scores and realistic expertise scores. However, no significant differences were observed in terms of negative and positive emotions nor in cognitive learning among the three different groups.

5. Conclusions

The convergence of artificial intelligence with augmented reality and virtual reality technologies is being increasingly examined. Due to the benefits they can bring in the educational domain, emphasis is put on their role and integration into teaching and learning. This study aimed at examining the existing literature to present the state of the art regarding the combination of artificial intelligence with augmented reality and virtual reality technologies and its use in education and to reveal future research areas. As a result, using two databases, documents relevant to the topic were identified, processed, and analyzed using various tools and approaches. Specifically, this study explored the existing literature in terms of the main characteristics of the relevant documents, that is, publication frequency, citation, count, authors, countries, affiliations, and sources. Additionally, this study looked into the most prominent topics regarding the integration of artificial intelligence, augmented reality, and virtual reality in education, examined the trend topics and thematic evolution of the topic, and highlighted the most popular themes and areas through the use of Bibliometrix, VOSviewer, and topic modeling.

Although efforts were made to offer a broader look at the existing literature, there are a few limitations that should be considered. Firstly, due to the tools used (e.g., Bibliometrix and VOSviewer), this study did not involve an in-depth content-wise analysis of the documents but focused primarily on the bibliometric data. Secondly, the documents were retrieved from two databases based on the aforementioned reasons. Thirdly, only English documents were analyzed. Hence, future studies should focus on examining more specific areas of this field through systematic literature review studies to explore the impact that the combination of artificial intelligence with extended reality technologies can have in education and how it can affect teaching and learning practices. Finally, specifying and identifying the number of topics is a challenge when using LDA; hence, a perplexity metric was used to specify a number of topics that yielded distinct topics representative of the document collection.

According to the results and focusing on the keyword and topic analysis, the potential of combining artificial intelligence with virtual reality and augmented reality can contribute to creating personalized, interactive, and immersive learning experiences. Due to their nature, these technologies can be used in all educational levels in both formal and informal settings supporting both students and teachers. The ability to create intelligent tutoring systems that have a virtual presence and can effectively play the role of a tutor or peer learner was evident. Additionally, such immersive intelligent tutoring systems can be regarded as affective and social entities with cognitive, social, and emotional skills that can provide personalized and affective learning. Through the behavioral personalization that they offer and their ability to recommend appropriate content and modify learning resources, material, and activities based on each learner's skills, knowledge, needs, and preferences, such systems can improve students' engagement, learning motivation, and academic performance. Additionally, they enable students to be engaged in experiential-based learning and problem-based learning through their involvement in hands-on activities within immersive and safe virtual environments. Hence, by combining these technologies, students take part in self-directed learning and in collaborative learning experiences and settings within virtual environments without which they would not have the opportunity to experience them. Although the combination of artificial intelligence with extended reality technologies is mostly being examined in the fields of computer science, medical and healthcare education, and in engineering, studies have also revealed its potential to be integrated in other domains as well.

Although the specific topic is in its infancy, it is rapidly advancing as can be concluded based on the significantly high annual growth rate (60.58%). The interest in the topic and the wider adoption and integration of artificial intelligence, augmented reality, and virtual reality in educational settings is expected to further increase in the coming years. Nonetheless, there is a clear need for more empirical, experiential, and case study-based studies to be conducted following appropriate methodologies and involving students' prolonged exposure to learning through the use of artificial intelligence and extended reality technologies. Future studies should also focus on identifying the most effective approaches to design such tools and systems, to create related educational material, and to effectively introduce them to classrooms. Additionally, emphasis should be put on how to integrate them in teaching and learning activities and on creating common guidelines and standards for others to adopt and follow. Moreover, and as the field of artificial intelligence is rapidly progressing, future studies should explore how to design and create effective, interactive, immersive, and customizable intelligent tutoring systems that can be integrated into extended reality environments that offer personalized learning experiences. Additionally, there is a need to evaluate how these technologies affect students' soft skills and knowledge acquisition. Given the social traits of immersive intelligent tutoring systems and their virtual presence, future studies should also look into how the virtual presence influences students' cognitive and socio-emotional development. Therefore, it is important to examine how the physical presence that characterizes some new technologies (e.g., social robots) compares to the virtual presence that extended reality technologies offer in terms of overall learning outcomes and students' development. Given the scope of this study and the keywords used, future studies should focus on further examining different types of artificial intelligence. Finally, it is also vital to explore how these technologies can affect learning design, evaluation, and assessment, as well as the role of teachers in an ever-increasing digitally enriched classroom.

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