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Review

Augmented Reality in Engineering Education: A Bibliometric Review

Georgios Lampropoulos [1,2], Antonio del Bosque [3], Pablo Fernández-Arias [3] and Diego Vergara [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, 2417 Nicosia, Cyprus
[3] Technology, Instruction and Design in Engineering and Education Research Group (TiDEE.rg), Catholic University of Ávila, C/Canteros s/n, 05005 Ávila, Spain; antonio.bosque@ucavila.es (A.d.B.); pablo.fernandezarias@ucavila.es (P.F.-A.)
* Correspondence: diego.vergara@ucavila.es

Abstract

The aim of this study is to examine the role and use of augmented reality in engineering education by examining the existing literature. A total of 235 studies from Scopus and Web of Science published during 2011–2025 were examined. The study focused on analyzing the main characteristics of the studies, identifying the main topics, and exploring the use of augmented reality in engineering education. The study also highlighted current challenges and limitations and suggested future research directions. Based on the results, 7 main topics arose which were related to (i) Immersive technologies in engineering education, (ii) Gamified learning experiences, (iii) Remote and virtual laboratories, (iv) Visualization and 3D modeling, (v) Student motivation, (vi) Collaborative and interactive learning environments, and (vii) User-centered design and user experience. Augmented reality emerged as an effective educational tool that can positively impact engineering education and support both students and teachers. Specifically, physical, remote, and virtual laboratories that can improve students' learning performance, motivation, creativity, engagement, and satisfaction can be created through augmented reality. Using augmented reality, students can develop their practical skills and knowledge within low-risk and secure learning environments. Additionally, via the realistic and interactive visualization, students' knowledge acquisition and understanding can be enhanced. Finally, its ability to effectively support collaborative learning and experiential learning arose.

Keywords: augmented reality; AR; mixed reality; extended reality; engineering education; virtual laboratories; remote laboratories; simulations; education; teaching; learning

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1. Introduction

The technological advancements and the changes to the industrial sector have brought about the need to re-examine the skills, knowledge, and competences that future engineers need to develop and how to more effectively cultivate them in educational settings [1,2]. Engineering education focuses on equipping students with engineering knowledge, principles, and skills necessary by combining foundational studies, specialized training, and hands-on experience to address real-world challenges and benefit society. Hence, engineering education is closely related to Education 4.0 in which the use of novel pedagogical approaches and digital tools is essential [3]. As engineers are trained to tackle complex global

challenges that have societal influence [4], emphasis is placed on cultivating engineering students' strategic, normative, and systems thinking competences and providing them with opportunities to understand and navigate the technological, societal, and environmental implications of their work [5,6].

Due to its complex and hands-on nature, for engineering education to be effective, students' learning motivation and engagement should be promoted since students need to play an active role in the learning process. Hence, it is important to adopt suitable learner-centered approaches that encourage students' active and meaningful participation [7,8]. Furthermore, as engineering education constitutes a multidisciplinary field of study which contains complex theoretical concepts and practical applications [9], it is becoming increasingly important for engineering students to develop their critical thinking, reasoning, and soft skills [10–12] as well as to acquire hands-on experience in problem-based and practice-oriented learning experiences that simulate closely real-world problems [13]. Given the nature of engineering education, providing students with the ability to apply theoretical concepts, practice and develop practical skills, and improve their knowledge and skills within immersive, virtual, and secure environments could positively influence their learning outcomes. Showcasing great potential to enhance engineering education and improve students' learning gains, virtual laboratories are more commonly being used in engineering education as they can be used both independently and as a supplement to physical laboratories [14,15]. In this context, it is clear that the pedagogical approaches used, the teaching methods and strategies adopted, and the tools used during learning activities can influence students' learning of engineering concepts [16,17].

Augmented reality has shown great potential to improve the educational process and enrich teaching and learning practices [18] since it can affect students' cognitive and social-emotional skills. As a result, it is being used in a variety of subjects and domains, including engineering education [19]. Specifically, in the context of education, augmented reality focuses on creating interactive digital information and objects and embedding them into learners' physical environment to transform the educational process and facilitate the comprehension of abstract concepts through immersive, multimodal, and hands-on experiences and through interactive representations [20–23]. When using augmented reality in education, students can safely experience real-world scenarios and environments and engage in experiential learning activities within them which, in turn, can influence their knowledge acquisition, critical thinking skills, creativity, and performance [24–27]. Additionally, augmented reality supports multiple representations of objects which can enhance students' understanding of complex concepts and improve their cognitive skills [28,29]. Augmented reality can also be used in conjunction with educational data mining and learning analytics techniques to offer personalized learning experiences [30]. As a result, when learning using augmented reality, students demonstrate increased learning outcomes, motivation, and engagement across subjects and levels [31,32].

Due to its traits, the role and use of augmented reality in engineering education are actively being examined. Recent studies have highlighted the potential of augmented reality to effectively support engineering education [33,34]. Moreover, studies have revealed the ability of augmented reality to offer interactive learning experiences that can enhance students' motivation in engineering learning [35] and improve students' learning [36], particularly in higher education [37]. However, as the field advances and more research is being conducted into this topic, it is important to map the existing literature. Although there are several studies that have examined the use of augmented reality in engineering education, to the best of our knowledge, there has not been any study that provides an overview of the field through a bibliometric analysis and scientific mapping approach. Suhail et al. [36] carried out a bibliometric analysis about the use of augmented reality in

engineering education; however, in their study, they have used only data from Scopus and up to 2023, utilized VOSviewer v1.6.28 to carry out the keyword analysis, and focused on an in-depth content analysis based on the related documents identified. Another important consideration is that the study searched for related documents only in the title field which, in turn, resulted in only 71 documents being identified and 67 being regarded as relevant. When, in our study, 1827 related documents were identified from Scopus and 263 from Web of Science (WoS) since the search query looked into the title, abstract, and keywords of the related documents which ensured that all related documents published in the specific databases would be identified. Additionally, the study of Álvarez-Marín & Velázquez-Iturbide [33], focused on a systematic review of the existing literature and on addressing five research questions which were related to AR interventions in engineering education. Our study differs from the existing ones as it utilizes a broader query and searches for related documents within two databases up to 2025. Additionally, as it does not focus on content analysis but, instead, on the bibliometric analysis of the related documents, it involves more flexible inclusion and exclusion criterion so that it analyzes and presents the use of augmented reality in engineering education from a broader perspective. This approach also enables the identification of key themes within the literature. Therefore, this study aims to provide a bibliometric review of augmented reality in engineering education by examining the existing literature. The study adopts a systematic approach to identify and select relative to the topic documents and then utilizes Bibliometrix to examine them while focusing on their main characteristics. The study contributes to the existing literature by examining the key characteristics of relevant to the topic studies (e.g., publication year, country, sources, citations, etc.), identifying key studies within the literature, revealing emerging themes and topics, and providing suggestions for future research.

2. Materials and Methods

Given the broad and general scope of the study, a bibliometric analysis and a scientific mapping approach was selected as the most appropriate approach to explore the related literature on a broadly defined topic [38] as is the examination of augmented reality in engineering education. Additionally, when reporting data from the literature, it is important to adopt reproducible, valid, and transparent approaches. Hence, suitable guidelines were followed [39] and the PRISMA framework was selected due to its rigor and it being widely used in other similar studies [40]. The specific framework was selected over other related frameworks due to it being more widely used in bibliometric review studies.

To identify relevant documents, Scopus and WoS were selected as the main databases as they are widely used in other related studies, they are highly regarded, index quality outlets, and contain relevant documents [41,42]. The generated outcomes of these databases can also be used by Bibliometrix [43], which is the tool used to analyze the data in this study, without requiring further adjustments which, in turn, increases the reproducibility of our study. Although these databases index sources that are highly regarded and publish quality manuscript, searching only within these two databases could be regarded as another limitation of this study since any potentially related document not indexed within them has not been retrieved.

The query was last used in July 2025 and was the following: (“augmented reality” OR “AR”) AND (“engineering education”). It should be noted that since the data reported only contained information about the first half of 2025, this can be regarded as a potential limitation. However, it enables better understanding of how the field advances in different intervals. Only data from 2010 onwards was considered to ensure the analysis captures contemporary research trends while still offering insights into the field’s development over time. It is worth mentioning that the query was kept basic without adding more keywords

to the second clause not to shift the outcomes to any given direction through the use of targeted keywords and do be in line with the scope and aims of this study. For example, keywords, such as "higher education", "professional training", etc., were not used since the goal was to examine documents of all educational levels without affecting the distribution using specific keywords. Similarly, no keywords dedicated to specific engineering disciplines were used to, once again, not affect the distribution of the documents. In this sense, related documents would already have mentioned the term "engineering education" within their title, abstract, and keywords which were the fields in which the query ran on. However, although the use of abbreviations (e.g., "AR") as well as searching in the keywords ensured that all related to the topic documents would be identified, many out of scope documents were also initially retrieved and later removed during the first stage of the eligibility assessment. Given the aim of the study and its broad focus, the inclusion criterion set was for the documents to focus on engineering education and on using augmented reality. However, due to the close relation of extended reality technologies, studies that primarily focused on augmented reality but also explored virtual, mixed, or extended reality were also included to provide a more comprehensive perspective. Based on the scope of this study and its aim to examine this broad topic through a bibliometric analysis, the specific inclusion criterion ensured that all related studies would be included and simultaneously, the ones that were removed would be completely outside the scope of using augmented reality in engineering education.

The detailed PRISMA flowchart is presented in Figure 1 and as it can be seen, 1827 documents from Scopus and 263 from WoS were identified. Hence, the document collection initially contained 2090 documents and after removing the duplicates identified (n = 219), a total of 1871 documents remained which were further examined for eligibility based on their title and abstract. To identify the duplicate documents, the title and DOI of the documents were examined. Additionally, the average citations between those reported in Scopus and WoS was calculated for the duplicate documents. From the remaining 1871 documents, 1580 were removed as they were out of scope and did not meet the inclusion criterion, 21 were removed as they were proceedings or edited book collections, 2 were removed as they were not written in English, and 1 was removed as it was an Editorial. Therefore, 267 documents remained and they were assessed for eligibility based on their full text. After examining the full text of the documents, a total of 32 documents were deemed out of scope since they did not meet the inclusion criterion and as a result, the document collection examined in this study consists of 235 documents.

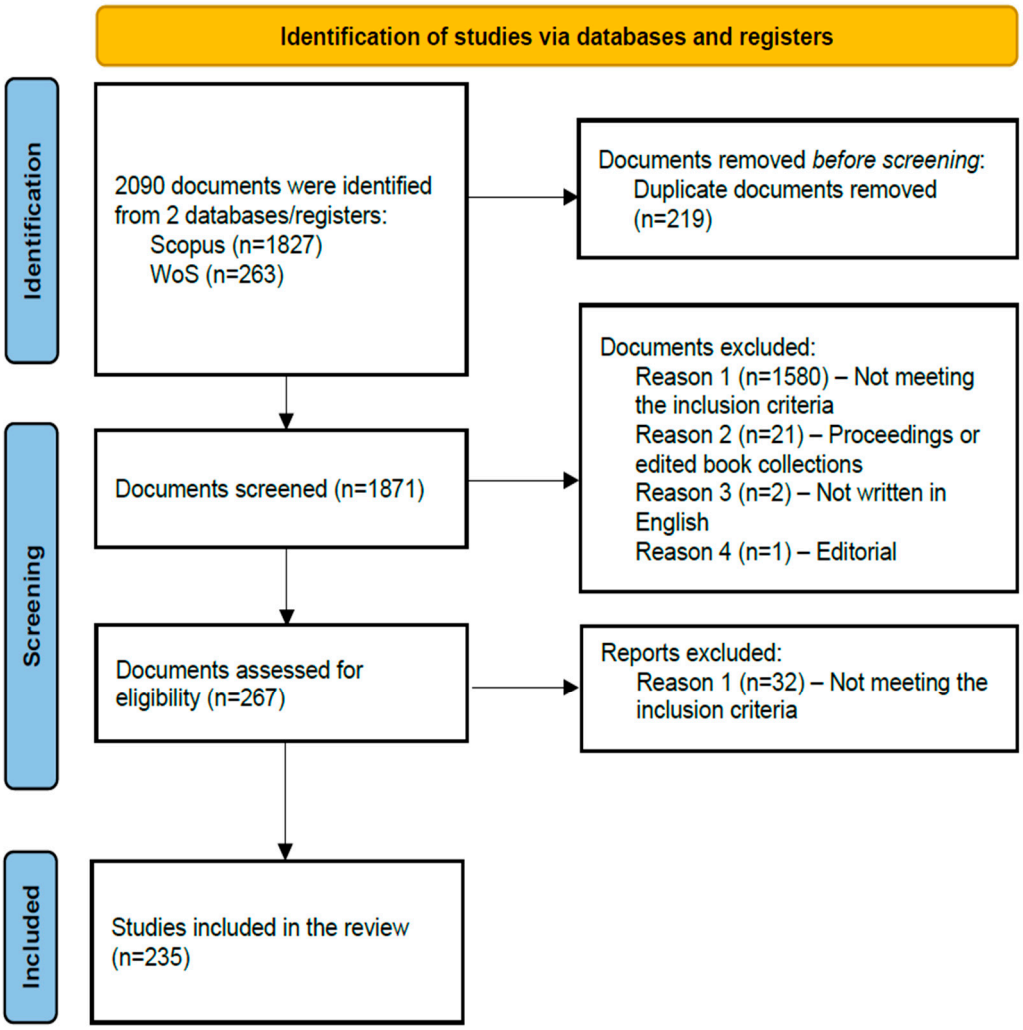


Figure 1. PRISMA flowchart.

3. Result Analysis

3.1. Analysis of the Document Collection

Following the data reported by the two databases, the 235 documents were examined as can be seen in Table 1. Although the search focused on documents that were published from 2010 onwards, the first related document was published in 2011. Therefore, the document collection consists of documents that were published from January 2011 to June 2025, had an average age of 3.91 years, and received 9.59 citations on average. The annual growth rate was 28.86% during 2011–2024 (the whole 2024) and 12.95% from 2011 to June 2025 (the first 6 months of 2025). This fact highlights the increasing interest in the topic and it being widely explored. The documents were published in 172 different sources, including journals, conferences, and book series. Specifically, 121 documents were published as conference/proceedings papers (51.5%), 87 were published as journal articles (37.0%), 15 were characterized as review studies (6.4%), and 12 were published as book chapters (5.1%). However, when we consider the difference in quality between the various conferences, the fact that most documents were published as conference/proceedings papers could influence the related outcomes and trend topics identified. The 235 documents were written by 688 authors from 49 different countries and had 3.51 co-authors on average. An international co-authorship rate of 13.62% was also observed. This fact indicates that there are some established international collaborations. A total of 19 studies were single-authored (8.1%) and were written by 19 different authors. Following Lotka's law, most

authors contributed to a single study (85.9%) while only a few contributed to 4 or more studies (0.7%) as can be seen in Table 2.

Table 1. Information regarding the document collection.

Description	Results	Description	Results
Main information about data		**Document types**	
Timespan	2011:2025	Journal articles	87
Sources (Journals, Books, etc.)	172	Book chapter	12
Documents	235	Conference/Proceedings paper	121
Annual Growth Rate % (2011–2024)	28.86	Review	15
Annual Growth Rate % (2011–2025 June)	12.95	**Authors**	
Document Average Age	3.91	Authors	688
Average Citations per Document	9.587	Authors of single-authored docs	19
References	3935	**Authors collaboration**	
Document contents		Single-authored docs	19
Keywords Plus (ID)	812	Co-Authors per Doc	3.51
Author's Keywords (DE)	600	International co-authorships %	13.62

Table 2. Lotka's law analysis.

Documents Written	N. of Authors	Proportion of Authors
1	591	0.859
2	75	0.109
3	14	0.02
4	5	0.007
5	1	0.001
6	1	0.001
12	1	0.001

3.2. Analysis of the Document Publication Year

Based on Figure 2, an increase in the number of published studies is observed from 2018 onwards. Hence, it can be inferred that from 2011 to 2017 (n = 32, 13.6%) it was the period in which the interest in this field started to appear while from 2018 onwards the field started to mature. More studies were published in 2023 (n = 36, 15.3%), 2022 (n = 32, 13.6%), and 2021 (n = 25, 10.6%) with the year 2024 showcasing a significant increase in published documents (n = 54, 23.0%). However, in the first six months of 2025 only 11 related documents were published (4.7%) which indicates a potential decrease in the number of published documents. Based on the mean total citations received per document which is presented in Table 3, the documents published in 2012 (MeanTCperDoc = 29.67), 2017 (MeanTCperDoc = 27.43), 2013 (MeanTCperDoc = 23.8) and 2019 (MeanTCperDoc = 23.75) received the most citations on average. However, the documents published in 2020 (MeanTCperDoc = 16.06), 2021 (MeanTCperDoc = 15.72), and 2015 (MeanTCperDoc = 14.33) have also showcased a relatively high number of average citations received. This fact further validates the lack of a definitive breakthrough time period for this field as its foundations are still being actively examined. However, it should be noted that this metric does not directly relate to the impact that all documents published in a year have as a whole. However, the related outcomes are expected to change as the field further advances.

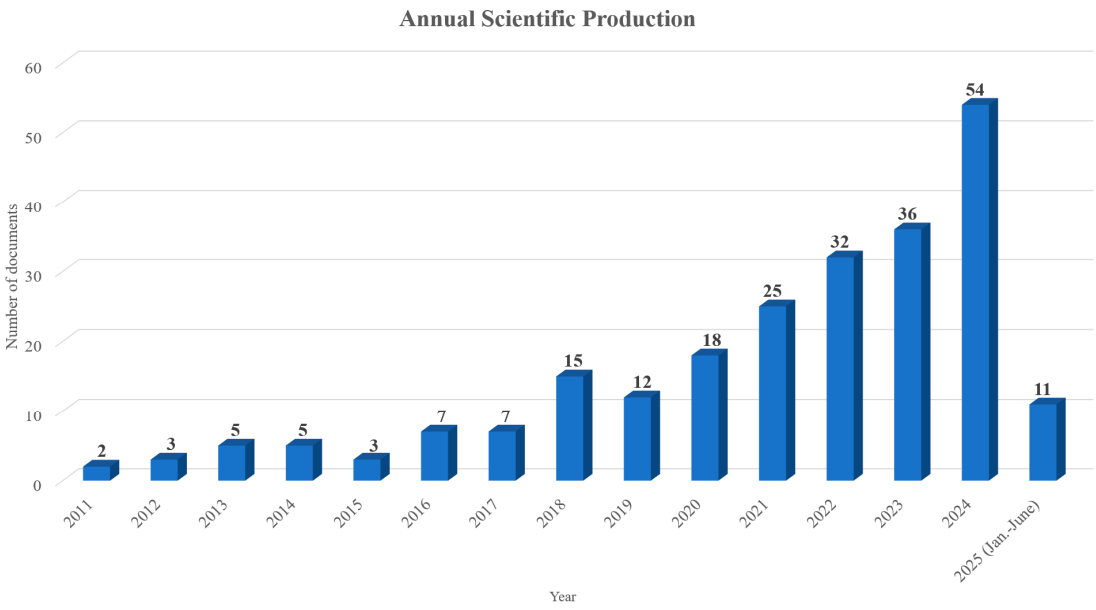


Figure 2. Number of documents published per year.

Table 3. Annual scientific production and citations.

Year	MeanTCperDoc	N	MeanTCperYear	CitableYears
2011	9	2	0.6	15
2012	29.67	3	2.12	14
2013	23.8	5	1.83	13
2014	11.6	5	0.97	12
2015	14.33	3	1.3	11
2016	11.71	7	1.17	10
2017	27.43	7	3.05	9
2018	11	15	1.38	8
2019	23.75	12	3.39	7
2020	16.06	18	2.68	6
2021	15.72	25	3.14	5
2022	7.62	32	1.91	4
2023	4.53	36	1.51	3
2024	2.06	54	1.03	2
2025	0.18	11	0.18	1

3.3. Analysis of the Sources in Which the Documents Were Published

Using Bradford's law, the 173 sources were categorized into three clusters from 1 to 3, with Cluster 1 having the most relevant sources based on the number of published documents on the topic. Specifically, Cluster 1 had 78 documents that were published in 26 sources (15.0%), Cluster 2 had 79 documents that were published in 68 sources (39.9%), and Cluster 3 had 78 documents that were published in 78 sources (45.1%). Moreover, Table 4 presents the sources that have published at least 3 related documents. "ASEE Annual Conference and Exposition, Conference Proceedings" (n = 9), "Computer Applications in Engineering Education" (n = 6), "IEEE Global Engineering Education Conference (EDUCON)" (n = 6), and "Education for Chemical Engineers" (n = 4) were the four sources with the most published documents on the field. "ACM International Conference Proceeding Series", "Education Sciences", "IEEE Transactions on Learning Technologies", "Interactive Learning Environments", "International Journal of Interactive Mobile Technologies", "International Conference on Interactive Computer Aided Learning (ICL)", "Smart Learning Environments", "Sustainability", and "TEM JOURNAL—Technology, Education,

Management, Informatics" each had 3 published documents. Based on the results of Table 5, "Computer Applications in Engineering Education" and "IEEE Global Engineering Education Conference (EDUCON)" were the two sources with the highest h-index on the topic. Having both conferences and journals among the top sources highlight the existence of active research communities that pursue the advancement of this field.

Table 4. Most impactful sources based on Bradford's law.

Source	Rank	Freq.	cumFreq.	Cluster
ASEE Annual Conference and Exposition, Conference Proceedings	1	9	9	1
Computer Applications in Engineering Education	2	6	15	1
IEEE Global Engineering Education Conference (EDUCON)	3	6	21	1
Education for Chemical Engineers	4	4	25	1
ACM International Conference Proceeding Series	5	3	28	1
Education Sciences	6	3	31	1
IEEE Transactions on Learning Technologies	7	3	34	1
Interactive Learning Environments	8	3	37	1
International Journal of Interactive Mobile Technologies	9	3	40	1
International Conference on Interactive Computer Aided Learning (ICL)	10	3	43	1
Smart Learning Environments	11	3	46	1
Sustainability	12	3	49	1
TEM JOURNAL—Technology, Education, Management, Informatics	13	3	52	1

Table 5. Most impactful sources based on h-index.

Sources	h-Index	g-Index	m-Index	TC	NP	PY-Start
Computer Applications in Engineering Education	4	6	0.5	117	6	2018
IEEE Global Engineering Education Conference (EDUCON)	4	6	0.286	101	6	2012
Education for Chemical Engineers	3	4	0.6	65	4	2021
Education Sciences	3	3	0.6	22	3	2021
Interactive Learning Environments	3	3	0.75	53	3	2022
International Journal of Interactive Mobile Technologies	3	3	0.6	68	3	2021
Smart Learning Environments	3	3	0.75	48	3	2022

3.4. Analysis of the Authors' Country

Furthermore, the corresponding author's country or in case no corresponding author was specified the country of the first author was examined to identify the countries that mostly publish on this topic. As it can be seen in Table 6, the United States (n = 35), India (n = 31), and Germany (n = 20) were the countries that contributed the most documents from the 49 countries identified. Additionally, China, Indonesia, Spain, and Malaysia each contributed at least 10 documents, followed by the United Kingdom (n = 7), Austria (n = 6), and Portugal (n = 6). Furthermore, the studies from India received the highest total citations (TC = 313), followed by those from the United States (TC = 246). Studies from Spain, Germany, China, Chile, and Indonesia also received over 100 TC as can be seen in Table 7.

Regarding the intra-country (SCP) collaboration and inter-country (MCP) collaboration among countries, the United States (SCP = 33) and India (SCP = 28) had the highest SCP among the countries followed by Germany (SCP = 19), Spain (SCP = 11), China, Indonesia, and Malaysia which all had an SCP of 10. Chile had the highest MCP (MCP = 5), followed by India (MCP = 3), the United States, China, Indonesia, Mexico, and Italy which all had an

MCP of 2. When considering the international co-authorships rate being 13.62%, 9 clusters of collaborators arose which are presented in Figure 3.

Table 6. Country publication details.

Country	Documents	SCP	MCP	Freq.	MCP_Ratio
United States	35	33	2	0.149	0.057
India	31	28	3	0.132	0.097
Germany	20	19	1	0.085	0.05
China	12	10	2	0.051	0.167
Indonesia	12	10	2	0.051	0.167
Spain	12	11	1	0.051	0.083
Malaysia	10	10	0	0.043	0
United Kingdom	7	6	1	0.03	0.143
Austria	6	5	1	0.026	0.167
Portugal	6	6	0	0.026	0

Table 7. Countries that received the most citations.

Country	Total Citations	Average Document Citations
India	313	10.1
United States	246	7
Spain	199	16.6
Germany	179	8.9
China	149	12.4
Chile	118	23.6
Indonesia	112	9.3
Malaysia	83	8.3
United Kingdom	79	11.3
Portugal	77	12.8
Greece	75	15
Slovakia	74	18.5

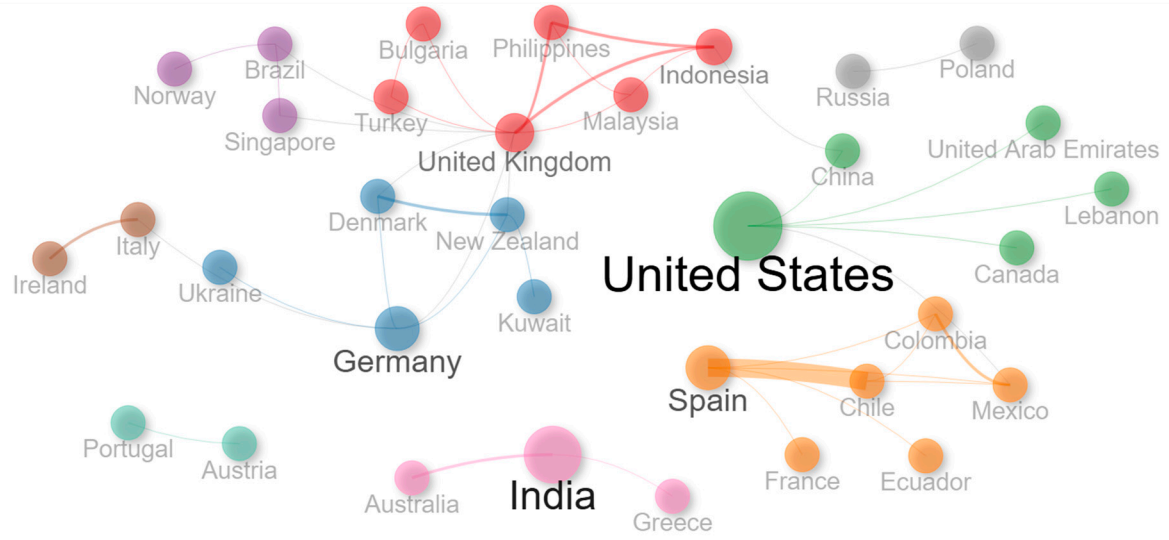


Figure 3. Country collaboration network.

3.5. Analysis of the Document with the Most Citations in the Collection

Focusing on the total citations received as reported from the two databases, the most widely cited documents were identified. The top-10 documents with the most citations are presented in Table 8 and are further examined in Section 4.

Table 8. Documents with the highest number of citations.

Document	DOI	Total Citations	Total Citations per Year	Normalized Total Citations
[44]	10.3390/app9091840	100	14.29	4.21
[45]	10.1016/j.promfg.2018.07.126	95	11.88	8.64
[46]	10.1016/j.advengsoft.2012.09.001	81	6.23	3.4
[47]	10.1007/s10956-011-9345-9	75	5.36	2.53
[48]	10.1002/cae.22156	64	9.14	2.69
[49]	10.1016/j.compedu.2017.02.009	60	6.67	2.19
[50]	10.1109/EDUCON.2017.7943075	60	6.67	2.19
[51]	10.1007/s12008-019-00640-0	59	9.83	3.67
[33]	10.1109/TLT.2022.3144356	53	10.6	3.37
[52]	N/A	49	4.08	4.22
[53]	10.1016/j.procs.2020.05.135	47	7.83	2.93
[54]	10.3390/app11114921	42	8.4	2.67

4. Discussion

Engineering education prepares students to solve real-world problems and benefit society by providing a blend of foundational theory, specialized training, and hands-on practice. As a field, it is constantly evolving in response to industrial, technological, and societal advancements [1,2,55]. To effectively train engineers for complex global challenges, education must adapt to these advancements, re-evaluate the core skills future engineers need, and embrace the principles of Education 4.0, which integrates novel teaching methods and digital tools to cultivate these competencies [1–3]. Additionally, it is important to provide engineering students with opportunities to understand the technological, societal, and environmental implications of their work [4–6].

Engineering education goes beyond cultivating students' technical knowledge and skills and focuses on developing their critical thinking, strategic, reasoning, and soft skills [10–12] by enabling them to learn through experiential learning settings that simulate real-world challenges [13] and by combining theoretical concepts with hands-on activities [9]. However, for engineering education to be effective students need to be actively involved and meaningfully participate in the learning process [7,8].

By blending the physical with the virtual world, augmented reality can create new learning experiences that enable engineering students to transition from theoretical knowledge to practical application, allowing students to develop and refine their skills effectively within immersive, interactive, and secure virtual learning environments. Through augmented reality, immersive learning environments, including remote and virtual laboratories, can be created which can be used either as standalone instructional tools or as supplements to traditional physical laboratories to effectively support engineering education [14,15].

Within these immersive environments and through the use of multiple, realistic, and dynamic representations of complex objects or systems that augmented reality offers, students can improve their knowledge acquisition, critical thinking, creativity, and academic performance [24–27] and achieve a deeper conceptual understanding which strengthens their overall cognitive skills [28,29]. Moreover, augmented reality can enhance teaching and learning activities [18], increase students' learning engagement and motivation [31,32,35], and improve their learning experience [36]. Recent studies that focused on the use of augmented reality in engineering education have highlighted the educational benefits it can yield and its ability to effectively support engineering education [33,34].

4.1. Main Topics Within the Literature

Given the multidisciplinary nature of engineering education and its multiple applications, in addition to the bibliometric data analysis, the keywords of the documents were

used along with the text and abstract of the documents to carry out topic analysis. For the keywords, both keywords plus and author keywords were used. Figures 4 and 5 present the most widely used keywords of each category. Specifically, the most frequently used keyword plus were "augmented reality", "engineering education", "students", "education", "virtual reality", "e-learning", "teaching", "curricula", "design", and "visualization". The most commonly used author keywords were "augmented reality", "engineering education", "education", "virtual reality", "engineering", "educational technology", "mixed reality", "higher education", "spatial ability", and "learning".

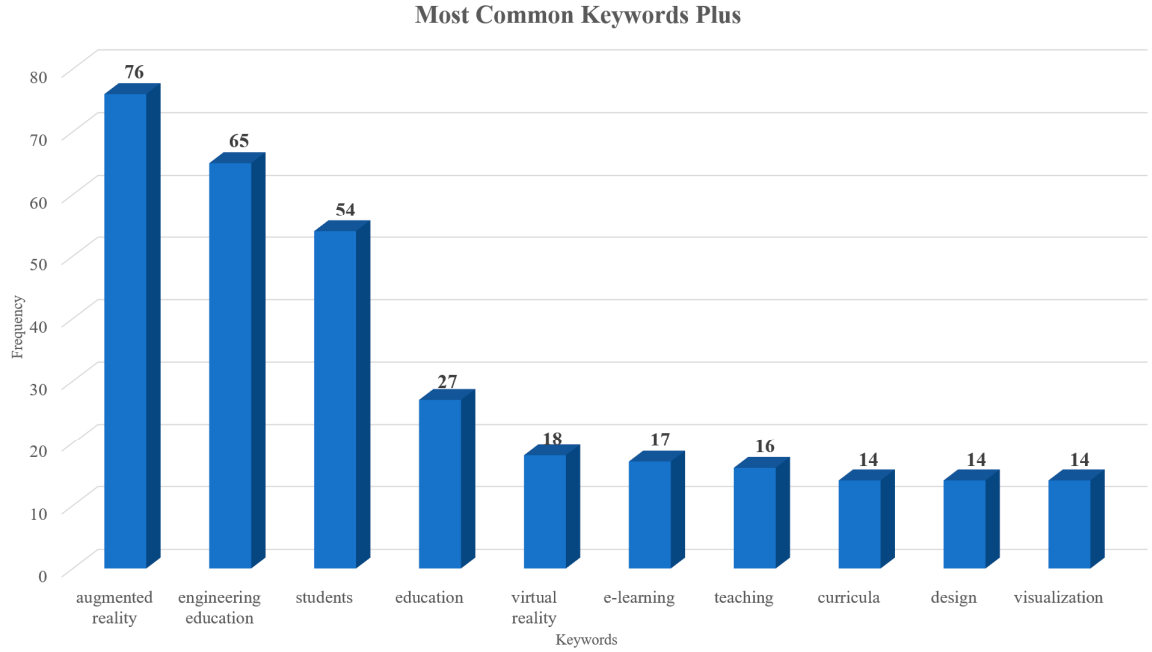


Figure 4. Most frequent keywords plus.

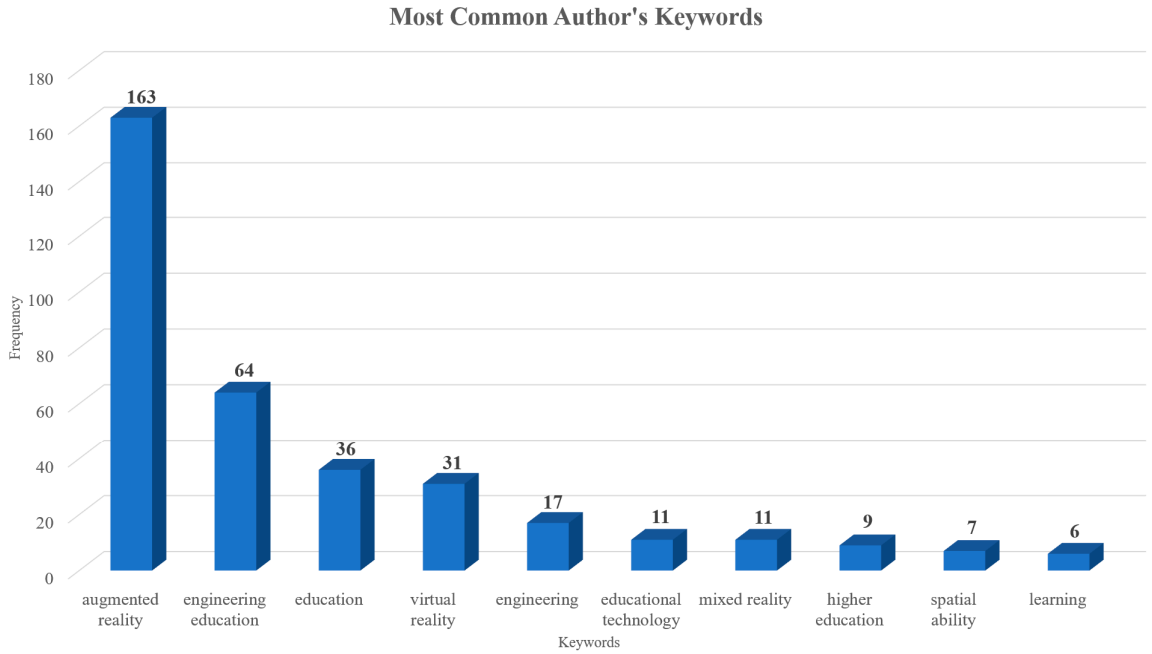


Figure 5. Most frequent author's keywords.

The relationship of the keywords was further examined through the creation of co-occurrence network which is presented in Figure 6. In total, the following three clusters arose:

- Blue cluster: 3d, 3d models, active learning, augmented reality, chemical engineering, civil engineering, educational technology, e-learning, engineering drawing, engineering education, experiential learning, extended reality, game-based learning, gamification, immersive learning, immersive technology, Industry 4.0, interactive learning environments, interactive learning, learning environment, mechanical engineering, metaverse, mixed reality, mobile applications, mobile application, motivation, motivational, simulation, skills, spatial ability, system, unity, virtual reality, and vuforia.
- Red cluster: collaboration, education, engineering, learning, mobile learning, teaching, technology, training, usability, and visualization.
- Green cluster: educational innovation and higher education

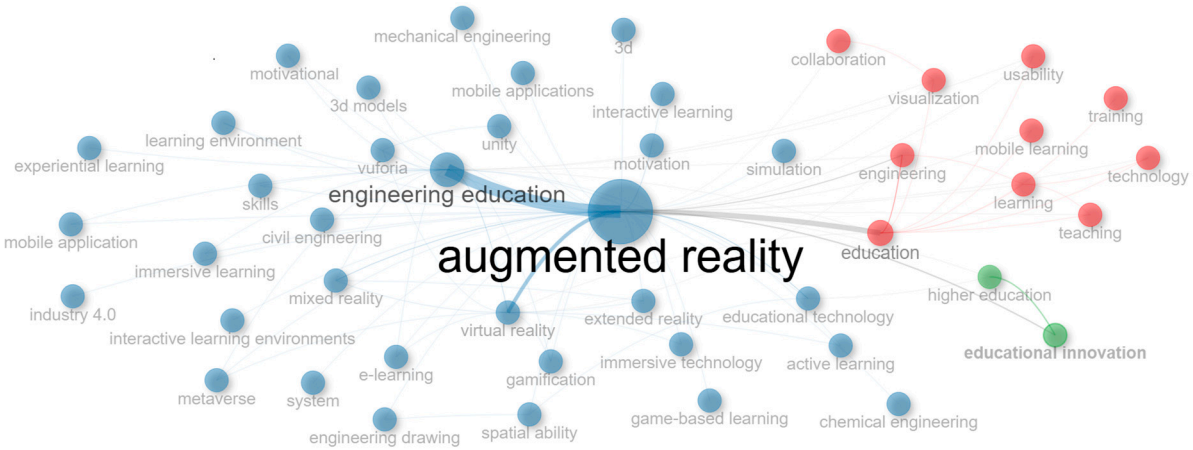


Figure 6. Keyword co-occurrence network.

Based on the aforementioned clusters, which were based on the keywords of the documents, and the document titles and abstracts, a topic analysis was carried out. In total, seven main topics arose which are related to:

- Immersive technologies in engineering education
- Gamified learning experiences
- Remote and virtual laboratories
- Visualization and 3D modeling
- Student motivation
- Collaborative and interactive learning environments
- User-centered design and user experience

Additionally, to better understand the topics of the collection, a thematic evolution and trend topic analysis was also carried out using Bibliometrix. When examining the thematic evolution of the topic, no profound evidence regarding the directions in which the topic heads for over the years was found. However, based on the related outcomes, it can be stated that there is a transition from emphasizing how augmented reality could be integrated into the curricula, to how it can affect students' learning motivation, how it can be used effectively for teaching, and how it can be integrated into existing learning systems. Finally, over the past few years, there has been an emphasis on how the information and educational content are visualized and presented to students. However, the trend topic analysis presents a clearer representation of the topics that are mostly examined in recent years as can be seen in Figure 7. Specifically, the initial emphasis on computer-

aided instructions shifted more profoundly on augmented reality, education, and learning performance starting from 2019. Thereafter, emphasis has been placed on how augmented reality can be used in teaching and learning, how it affects students in the context of engineering education and how it can be used in conjunction with other learning systems in the broader domain of educational technology. In recent years, there has been an increasing focus on 3D modeling within augmented reality environments, on creating realistic and immersive virtual laboratories, and on the impact that augmented reality has on various engineering disciplines. These outcomes are in line with key topics identified from the topic analysis. However, it is worth mentioning that since the topic analysis also included the document title and abstract, more topics with more specific details were identified. Particularly, when considering the topics identified, it is important to highlight the cohesion among the topics. For example, immersive technologies are closely related to gamified learning and gameful approaches and their combination can influence teaching and learning activities. Additionally, in the context of engineering education, developing and using virtual and remote laboratories, which can also integrate gamification aspects, is widely examined. Given the nature of augmented reality and other immersive technologies, their ability to provide realistic and interactive models and visualizations as well as to create opportunities for interactive, collaborative, and social learning is highly regarded. However, these environments require effective student-centered design approaches to be followed to foster students' motivation and participation. Nonetheless, augmented reality aligns with existing learning theories (e.g., experiential learning, constructivism, etc.) and can create effective virtual learning environments which enrich existing engineering educational practices. Hence, the topics identified from the topic analysis, although distinct in nature, they are highly interrelated with one another.

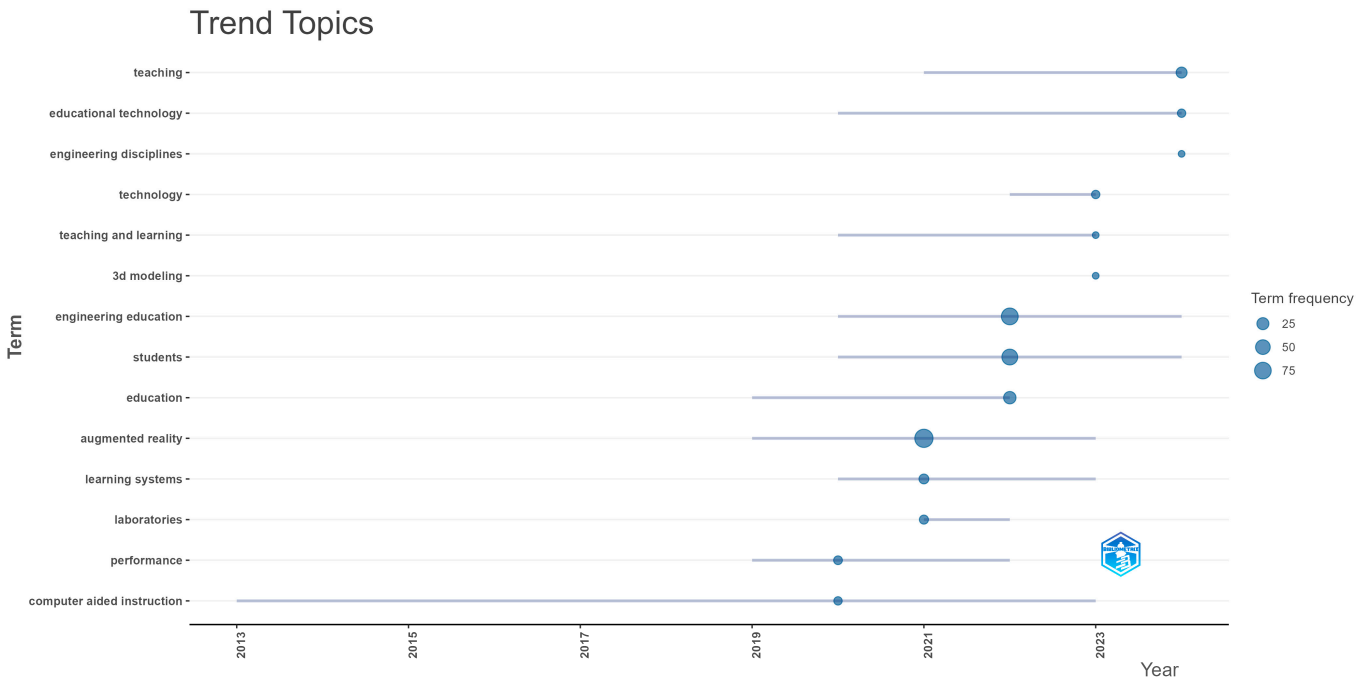


Figure 7. Trend topic analysis.

4.2. Presentation of the Studies Identified

Although this study focuses on a bibliometric analysis, to provide a better representation and understanding of the existing literature regarding the use of augmented reality in engineering education, the studies that received the most citations, which were presented in Table 8, were further explored. Despite the fact that only a limited number of studies are

presented, given the influence of these studies, helpful insights to better comprehend the impact of augmented reality on engineering education can be generated.

Specifically, Diao and Shih [44] explored the use of augmented reality in architectural and civil engineering education through a systematic review. Their results highlighted the educational and pedagogical benefits that the integration of augmented reality can bring about. Additionally, marker-based augmented reality, using mobile devices, such as smartphones or tablets, is primarily used. When learning using augmented reality in engineering education, emphasis is put on the learning tasks rather than the locations or the roles and project-based learning is mostly used. Finally, the study also revealed benefits and challenges associated with the integration of augmented reality in education. Grodotzki et al. [45] put emphasis on the use of remote and virtual laboratories in engineering education focusing on immersive technologies. The study presented the current state of the art regarding virtual laboratories and commented upon the existing limitations and challenges. The study suggests that augmented reality can significantly contribute to improving the quality of remote and virtual laboratories, thus enhancing engineering education.

Dong et al. [46] highlighted the role of augmented reality in offering collaborative visualization of engineering process. Specifically, they stated that the interactive experiences offered by augmented reality and the realistic representations can positively contribute to achieving effective collaborative learning. Focusing on enhancing electrical engineering education, Mejías Borrero and Andújar Márquez [47] examined the use of augmented reality. Specifically, their study revealed that augmented reality can be used to create student-centered remote and virtual laboratories that can positively influence both teachers and students. The study highlights that by using augmented reality new teaching and learning possibilities are enabled which would not be possible within traditional laboratories.

As augmented reality can support experiential learning, Singh et al. [48] assessed the impact of augmented reality on engineering students' laboratory skills in higher education. Their outcomes suggest that augmented reality has a significant positive influence on students' laboratory skills and that augmented reality tools can reduce students' cognitive load. The ability of students to practice their skills within virtual environments using digital equipment was highly regarded since students demonstrated reduced levels of anxiety and fear when using actual equipment without damaging it as they were already accustomed to using it within the virtual learning environments. Frank and Kapila [49] explored the integration of mobile interfaces within engineering education in the context of laboratory learning while emphasizing the use of mixed reality environments. The study focused on the use of augmented reality, multi-touch interactions, and vision-based measurement and control systems. Based on their outcomes, engineering students that learnt using augmented reality showcased a better understanding of control concepts, demonstrated improved knowledge of the concepts taught, and reported having better learning experiences. Dinis et al. [50] examined the use of game-based virtual and augmented reality applications in civil engineering education. Their results revealed that augmented reality applications can aid students in better understanding the concepts taught, improved their motivation, and enhanced their creativity.

Hernandez-de-Menendez et al. [51] explored the use of various emerging technologies in education, including augmented reality. The study highlights that augmented reality and other related technologies can positively affect education processes and lead to the creation of education that is flexible and exciting while providing students with new opportunities to practice their skills and enhance their knowledge. Álvarez-Marín and Velázquez-Iturbide [33] carried out a systematic literature review that explored the use of augmented reality in engineering education. The outcomes of the study highlighted that augmented reality can be an effective educational means in engineering education.

Specifically, it can be used in different aspects of engineering education, can be adopted in both lectures and laboratories, and its use can be influenced by students' and instructors' viewpoints and skills. The study pointed out that despite the low levels of interactivity observed in some augmented reality applications, students who learn through it achieve better academic performance. Finally, the study commented upon the need to focus on interactivity and higher functional characteristics when designing and developing augmented reality applications.

Gutiérrez and Fernández [52] explored the influence of augmented reality on students' learning motivation and academic performance in the context of engineering education. Their results revealed that students who learnt engineering concepts using augmented reality demonstrated a significant increase in their learning performance as well as in their learning motivation when compared to students who learn the same concepts using traditional methods. Arulanand et al. [53] focused on examining the use of augmented reality in engineering education. Specifically, they suggested a framework to effectively integrate augmented reality using mobile devices in laboratory courses. They suggested that through this approach, teaching and learning can be both more enjoyable and more effective. Finally, Criollo-C et al. [54] explored the new learning possibilities that become available when using augmented reality in engineering education. The study highlights the need to focus on the usability aspects associated with augmented reality applications as they can influence students' learning effectiveness and motivation. Their results revealed that students who learnt using augmented reality performed better than those who learnt using traditional approaches.

4.3. Outcomes and Implications

Due to the educational benefits that the use of augmented reality can yield in engineering education, the research into it and immersive technologies in general has been increasing with authors around the world examining its implications. Augmented reality can be used in different domains of engineering education. However, emphasis is being placed on its use in creating interactive remote and virtual laboratories and providing detailed and realistic visualizations and 3D models. Additionally, augmented reality can be used in conjunction with gamified learning approaches to further improve students' learning outcomes. Given the complexity of engineering education, there is an increasing focus on integrating augmented reality to enhance students' learning motivation. As augmented reality merges the virtual with the physical environments and enables users to interact with virtual content without restricting them from interacting with their physical surroundings, it creates unique opportunities for students to be involved in collaborative learning activities within interactive learning environments. Finally, emphasis is placed on adopting user-centered design approaches and improving user experience.

When applied in engineering education, augmented reality can result in the creation of more effective, flexible, exciting, and enjoyable learning experiences [51,53] that promote experiential learning, problem-based learning, and hands-on activities [44] in both laboratory and lecture courses [33]. Augmented reality provides new opportunities for collaborative learning [46] and offers safe, secure, and low-risk virtual environments for students to practice and develop their practical skills [47,48,51]. It can also enhance the quality of engineering education by enriching physical, remote, and virtual laboratories [45,47] and supporting both students and teachers [47].

When compared to students who learn using traditional methods, students that learn using augmented reality present increased learning outcomes and academic performance [33,52,54], enhanced learning motivation [50,52], satisfaction [49], and creativity [50], and improved practical skill development, knowledge acquisition, and concept under-

standing [48–51]. Simultaneously, through the immersive and interactive experience and realistic representations, augmented reality reduces students' cognitive load and decreases their anxiety and fear when using engineering equipment [46,48]. Therefore, it can be inferred that augmented reality is an effective educational tool that can positively impact engineering education.

Finally, the thematic analysis revealed the most prominent topics within the literature and highlighted the multifaceted nature of augmented reality. Specifically, the focus of integrating augmented reality into engineering education is placed on the immersive and gamified learning experiences that it can offer. These experiences have the potential to enhance students' learning engagement and motivation which are vital aspects in education and more so in more complex subjects, such as engineering. Therefore, attention is given on how to further increase students' engagement and motivation through augmented reality-based learning. Emphasis is also put on the augmented reality environments and experiences in themselves as augmented reality can support face-to-face, online, and blended learning environments and has shown great potential to create effective remote and virtual laboratories. Moreover, these environments can enrich existing teaching practices and also be used as an alternative to physical laboratories and provide opportunities for students to participate in hands-on activities when resources are scarce; thus, increasing access to education. Through its immersive and interactive experiences, augmented reality provides opportunities for meaningful learning of complex concepts which, in turn, can improve students' understanding, reasoning, skills, and knowledge. Hence, there is an increasing interest in the realistic and interactive 3D models and visualizations that are embedded in students' physical environment via augmented reality. Lastly, emphasis is being placed on the collaborative learning experiences that can be created through augmented reality as well as on identifying key design aspects and defining suitable user-centered development approaches that improve user experience and learning outcomes.

5. Conclusions

This study examined 235 documents published from January 2011 to June 2025 to analyze the role and use of augmented reality in engineering education. The outcomes revealed an increasing interest in the field. Most related documents were published in the last few years, which highlights the recency of the topic. Additionally, the distribution of citations points out the strong theoretical foundations that have been developed steadily over the years. It is important to note that both conference and journal sources arose among the top sources which highlight the existence of active research communities which pursue the advancement of this field. The global interest in the use of augmented reality in engineering education was observed as authors from 49 different countries contributed to the document collection. The United States, India, and Germany contributed the most documents on the topic. Documents from India, the United States, and Spain received the most total citations; however, the documents from Chile, Slovakia, and Spain had the highest number of average document citations.

Through the topic modeling, seven topics arose. Emphasis is being placed on the use of immersive technologies, including augmented reality and virtual reality, in engineering education. Due to the nature of augmented reality and its ability to blend the physical with the digital environment, its potential to create effective remote and virtual laboratories is highly regarded. Additionally, the enrichment of augmented reality learning experiences with gamification elements to improve students' learning motivation, enjoyment, and engagement was revealed. As augmented reality can offer realistic, detailed, interactive, and multimodal representations, emphasis is being placed on its use in the context of 3D modeling and visualization. Given the complexity of engineering education, the ability

of augmented reality to enhance students' active involvement and learning motivation is pointed out. The ability of augmented reality to create unique, interactive learning environments by combining the real with the virtual world that promotes collaborative learning and experiential learning was highlighted. Finally, the need to focus on improving user experience and adopting user-centered design approaches arose.

Based on the studies examined, it is suggested that augmented reality may offer benefits and enhance engineering education. By embedding digital information and interactive content into the physical environment, augmented reality creates dynamic, flexible, and engaging learning experiences that can overcome the limitations of traditional instructional methods. Augmented reality learning environments enable students to apply their theoretical knowledge and practice their skills within immersive, interactive, realistic, secure, and low-risk virtual environments. Furthermore, it supports collaborative learning, promotes experiential and hands-on learning, and offers realistic and interactive visualizations.

Based on the outcomes of the studies examined, engineering students learning via augmented reality demonstrated increased academic performance, knowledge acquisition, understanding, and practical skills in comparison to those who learnt using traditional methods. The use of augmented reality resulted in students' showcasing enhanced learning motivation, satisfaction, creativity, and involvement. Students that used augmented reality also had reduced cognitive load and levels of anxiety which is often associated with operating complex engineering equipment. Therefore, it can be inferred that augmented reality can constitute an effective educational tool that has demonstrated great potential to improve students' learning outcomes and efficiently support engineering education.

Despite its clear potential to make learning more tangible and accessible and prepare students for the technology-driven demands of the modern engineering profession, there are several challenges that need to be addressed before augmented reality becomes more widely used in engineering education. These are related to hardware and software limitations, to lack of equipment and training, students' potential cognitive overload and risks of distraction, and the varying technical readiness of education stakeholders. Other important issues are related to inclusivity and ethical concerns, to the equitable access, as well as the lack of standardized pedagogical frameworks, evaluation methods, and augmented reality-enabled quality educational content. Finally, designing effective augmented reality interfaces and experiences for engineering education presents significant challenges, particularly in aligning immersive content with pedagogical goals while maintaining cognitive clarity. Balancing interactivity, visual complexity, and instructional scaffolding is important to ensure that augmented improves the learning of complex engineering concepts.

Future studies should focus on developing clear guidelines, metrics, and standards for the effective design, development, implementation, and evaluation of augmented reality applications in educational settings while prioritizing user-centered approaches. There is also a need for longitudinal studies to be conducted to examine the long-term impacts of learning via augmented reality. Besides students' academic performance, emphasis should also be placed on other learning related factors, including engagement, motivation, collaboration, and interest, as well as how learning through augmented reality might influence students' cognitive development and professional competence. It is particularly important to have studies that assess these factors in different settings and context to better understand the influence of augmented reality on students. Comparative studies between augmented reality and other immersive technologies, such as virtual reality, are essential to understand their relative benefits and limitations. It is also important to explore the socio-economic factors influencing the adoption of augmented reality, including cost-effectiveness, scalability, security, and inclusivity. Future studies should focus on carrying out more in-depth systematic literature reviews and content analyses to examine

the pedagogical frameworks, approaches, tasks, and devices used as well as exploring the characteristics of the augmented reality environments (e.g., multi-user, collaborative, or individual) and the specific domains of engineering in which the use of augmented reality could be more beneficial. Additionally, there is a need for more comprehensive meta-analysis studies to be conducted to evaluate the impact of augmented reality on students' learning outcomes. Based on the results of the topic analysis, it can be inferred that future studies should emphasize exploring the use of various immersive technologies in engineering education, how to adopt gamification in the learning process, and how to effectively design and create virtual and remote laboratories as well as interactive models and visualization. Studies should also focus on identifying suitable user-centered design approaches that could aid in the creation of interactive and collaborative learning experiences and improve students' learning experience and foster their learning motivation and engagement. Finally, it should be highlighted that collaboration among education stakeholders, technologists, and industry partners is important to ensure that augmented reality solutions align with real-world engineering practices and educational needs.

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