Trends of Augmented Reality Applications in Science Education: A Systematic Review from 2007 to 2022

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Abstract—A systematic literature review in the field of augmented reality (AR) in science education was conducted in the study. We performed a content analysis of 319 refereed articles from the Scopus database over the last 15 years (2007-2022). By adopting Cooper's guidelines, trends of AR applications in science education were viewed from various aspects, such as annual scientific growth, the number of authors, most active countries, most prolific journals, most cited articles, and most preferred research methods. The results indicated that: (1) research on AR applications has steadily increased since 2007 and peaked in 2020 and 2021; (2) the majority of publications have two authors followed by three authors and four authors; (3) the countries of the first authors of the AR studies were mostly from the US followed by Taiwan and Turkey; (4) the majority of articles were published by the *Journal of Chemical Education* and *Computers and Education* with 19 and 11 papers, respectively; (5) the most cited papers were written by Dunleavy, Dede, and Mitchell (638 citations), Potkonjak and colleagues (339 citations), and Squire and Jan (300 citations); and (6) more than one-third of the documents employed quantitative methods followed by mixed and qualitative methods. Discussion and suggestions are presented for future studies.

Keywords—augmented reality, science education, systematic analysis, literature review, research trends

1 Introduction

In the last three decades, augmented reality (AR) has been widely used as an interactive technology in various learning and educational settings. One of the most important reasons that AR technology is broadly utilized is that it can be used on various platforms such as desktops, tablets, smartphones, and notebooks. In a study, Klopfer and Squire [1] define AR as "a situation in which a real-world context is dynamically overlaid with coherent location or context-sensitive virtual information" (p. 205). As a popular technology tool, AR is extensively adopted at all levels of education [2]–[6]. Because it is useful for educational purposes, the use of AR has also been examined across disciplines, for example, in physics [4], biology [5], chemistry [6], and mathematics [7]. In general, AR is utilized to make connections between virtual objects and the real environment in order to simplify and clarify the visualization of complex materials [8]. This combination of virtual objects and the real world is referred to as "mixed reality", which was first introduced in the 1990s as a training tool as well as a new approach to education [9]. Since then, AR has continued to receive massive attention and study. However, despite the increasing popularity of AR studies in science education among researchers, understanding of research outputs, author numbers, most productive countries and journals, most-cited papers, and methodological trends of AR research is still limited. Limited understanding in this area may hinder the development of future AR studies. Thus, the current review fills this gap to guide future studies as well as serve as a reference point for AR researchers, policymakers, and educators in the field of science education.

2 Literature review

As a system, Azuma et al. [10] describe three important properties of AR, such as "(a) combines real and virtual objects in a real environment, (b) runs interactively, and in real-time, and (b) registers real and virtual objects with each other" (p. 34). According to the characteristics of the AR system, previous literature reported the main benefits of AR, such as effectively stimulating interest and increasing achievement and motivation to learn science [11][12]. In short, AR has offered potential opportunities for students to see the world around them in new ways thereby providing an engaging learning experience [13][14]. More importantly, AR provides a more realistic learning experience and helps students to be actively involved in authentic explorations in their real-life [15]. Thus, AR is believed to increase understanding of abstract concepts [16], improve spatial cognition abilities [17], reduce cognitive load [4], and make it easier for students to understand context-specific skills and knowledge [18].

As AR is believed to be effective in enriching teaching and learning experiences, literature reviews on the uses of AR have been documented in recent years. For example, Arici et al. [19] conducted content and bibliometric mapping analysis of 79 documents from the Web of Science (WoS) database in the period 2013-2018. The study revealed research trends over the last six years by content analysis and examined bibliometric results of articles related to the uses of AR in science education. Results showed that (i) the most cited journal is Computers & Education, (ii) quantitative design is the most used research method, and (iii) Azuma, Dunleavy, and Klopfer are the most cited authors in this area. Similarly, Tezer et al. [20] reviewed 1008 documents published (2001-2019) in various databases. They found that (i) researchers from the US have the most publications, followed by Taiwan and Germany, (ii) a quarter of publications have two authors, and (iii) qualitative methods are used more frequently than quantitative methods. In another contribution, Sirakaya and Sirakaya [21] reviewed 105 articles published between 2011 and 2016 from ERIC, EBSCOhost, and ScienceDirect databases. They reported that (i) the number of AR studies has increased over the years with a peak in 2016 and (ii) quantitative methods are more frequently adopted in publications, followed by literature review and mixed methods. Altinpulluk [22] reviewed 58 articles published (2006-2016) in 8 reputable journals from the WoS database. The author found that (i) no articles were published in 2006 and 2010, (ii) the most widely used method is mixed-method, followed by quantitative and design-based methods, and (iii) Taiwan has the largest number of publications, followed by the US and Spain. Lastly, Chen et al. [23] reviewed 55 articles published (2011–2016) from the WoS database. They reported that (i) most of the research was published in 2018, (ii) the most productive journals are Computers & Education, followed by Computers in Human Behavior, and Journal of Science Education and Technology, (iii) the Taiwanese researchers contributed the most articles followed by Spanish and US researchers, and (iv) the most frequently employed of research methods is mixed methods, followed by quantitative and qualitative methods.

The aforementioned literature describes in detail the current state of AR use in education; thus, they make a valuable contribution to the trends in this field. When trend research in the previous literature is analyzed [19]−[23], it can be observed that the variables examined are similar to those in this review. However, the current status of the use of AR in science education has not been reported. It should be noted that previous evidence identified AR publications up to 2019. In addition, previous studies indicated that trends and results of studies on AR usage in education, particularly in science education, were unclear. Hence, the current review focuses on applications of AR in science education research published from 2007 onwards. These documents were then analyzed with respect to examined variables, such as annual scientific growth and author numbers. In addition, the most productive countries, most productive journals, most cited papers, and most preferred research methods were examined. It is clear that the increasing volume of empirical studies in AR applications requires a comprehensive and systematic synthesis. Subsequently, a comprehensive review of AR research in science education is addressed. In the existing literature, science education is defined as a discipline related to the teaching and learning of science in schools, colleges, and universities [24]. Science is a field of education where AR technology is frequently adopted. Subjects included in science education are chemistry, biology, and physics. By considering recent peer-reviewed journal articles related to the uses of AR for teaching and learning, the current review aims to complement previous studies and improve the literature on research trends and patterns of AR in science education.

Specifically, this study aims to capture and map the latest trends in usability research in AR in the last 15 years. For this purpose, we performed an extensive literature review. Through this comprehensive systematic review, the current findings are expected to make a valuable contribution to policymakers, researchers, and educators studying the use of AR in science education. Also, it is intended to reveal the results that will shed light on future studies. In order to accomplish this goal, the research questions (RQs) set out in the current study are:

- RQ1: What is the annual scientific growth rate of publications on the topic of AR in science education between 2007 and 2022?

- RQ2: How is the distribution of the documents reviewed with regard to the number of authors in the 2007-2022 period?
- RQ3: Which countries contributed the most to the publications in the academic journals from 2007 to 2022?
- RQ4: Which are the most productive journals publishing articles on the applications of AR in science education between 2007 and 2022?
- RQ5: Which are the most cited articles related to the applications of AR in science education in the 2007-2022 period?
- RQ6: What were the most preferred research methods in articles on the applications of AR in science education from 2007 to 2022?

3 Methods

To address research questions, we conducted a systematic review using content analysis. As stated by Petticrew and Roberts [25], a systematic literature review should "comprehensively identify, appraise and synthesize all relevant studies on a given topic". Specifically, content analysis was used to make repeatable and valid deductions from texts concerning their contents in a particular field [26]. In this review, we then followed Cooper's [27] guidelines to conduct a systematic content analysis; (1) formulate the research problem, (2) collect data, (3) evaluate the data, (4) analyze the data, and (5) present the results. It aimed at presenting a comprehensive overview of the literature on the use of AR in science education.

3.1 Data collection

The search process was carried out in the Scopus database—one of the most prestigious journal article collections—on February 24, 2022. Scopus is a world-class database that includes high-quality journals and holds daily updates enabling the discovery of peer-reviewed articles. The Scopus database was preferred because it provides appropriate data for systematic review purposes. The date range was determined as 2007–2022 at a 15-year interval to ensure that there were sufficient data to analyze research patterns and trends. The year 2007 was chosen as the baseline due to the fact that studies on the use of AR in education began to develop gradually [22]. In the initial search, there were 1573 journal articles found using Boolean commands based on Title-Abstract-Keywords search: "Augmented Reality" AND "Science" OR "Chemistry" OR "Biology" OR "Physics" AND "Education" OR "Learning" OR "Teachers" OR "Students". The review was restricted to English peer-reviewed journal articles. In addition, they had to meet the following inclusion criteria: a) published in a reputable academic journal, b) discussed the application of AR in science education, c) published during the last fifteen years, and d) indexed in the Scopus database. Only articles with access to the full text were included. In this review, the authors set exclusion criteria for the following types of documents: conference paper, conference review, review, book chapter, book, editorial, note, and erratum to accurately identify the final articles. After the initial screening, a total of 461 published papers that met the research criteria were identified. After meeting the inclusion and exclusion criteria, the full text of all articles was then downloaded. The identified articles were read and analyzed to ensure that these articles were truly related to AR in science education. Each paper was checked by all researchers, taking into account the inclusion and exclusion criteria. We further removed any paper that did not meet the inclusion criteria, which was reduced to 319 papers. All articles were analyzed to answer the research questions.

3.2 Data analysis

In the current study, we adopted descriptive content analysis [28] as the analytical method. Content analysis is a method that involves coding, creating meaningful categories, comparing categories and making connections between them, and concluding and interpreting results [29]. This study focused on applications of AR in science education articles published between 2007 and 2022. All selected articles were next analyzed in terms of annual scientific production, author numbers, most cited papers, and nationality of the first author. In previous studies, the first author is seen as the individual who made the most significant intellectual contribution to the design and implementation of the study and development of the paper [30][31]. As such, we awarded one credit point only to the first author in selected papers. Also, the most productive journals and method trends were investigated in this review. For example, the coding scheme for research methods included quantitative, qualitative, mixed, and non-empirical methods.

The screening was based on titles, abstracts, and full texts. A total of 319 articles published from January 2007 to February 2022 were analyzed in the study. In the coding scheme stage, the first and second researchers read each document carefully and then started to code independently. After that, all researchers checked and discussed the inconsistent coding results and negotiated to reach a consensus. The inter-rater coding agreement was found to be 93%. The information obtained from each article reviewed was then inputted and organized through Microsoft Excel according to the research questions. Aiming at analyzing the findings, descriptive statistics were also employed. Frequencies and percentages were presented in graphics and tables.

4 Findings

The current study is intended to map the research characteristics of previous studies investigating AR applications in science education. In this section, we will discuss the findings of the study based on six proposed research questions.

4.1 Annual scientific growth

A total of 319 articles have been published in the Scopus database from 2007 to 2022. To answer the first research question, we analyzed the volume of annual publications in AR research. Figure 1 depicts the number of papers published per year. The annual number of publications is increasing over the past 15 years but with some fluctuations.

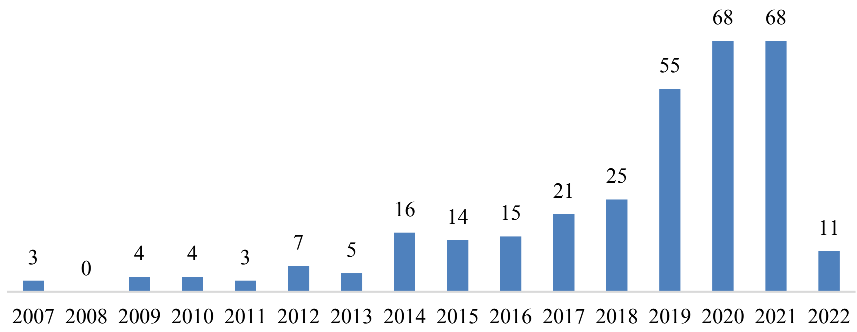

Fig. 1. Frequency of publications in augmented reality

The number of articles by year can be seen in Figure 1. Figure 1 illustrates the trend of publications since 2007. A total of 3 papers were recorded in 2007, indicating the beginning of the growth of publications in the field. No output appeared in 2008, while 2020 and 2021 had the highest productivity with 68 papers each. Since the dataset was taken at the end of February 2022, the number of papers for 2022 was less than for the last 15 years. A significant increase in the number of articles was seen from 2018 to 2020, where 2020 and 2021 were the most productive years. According to Figure 1, 2019 (n = 55), 2020 (n = 68), and 2021 (n = 68) saw a sharp increase in publications. In total, 59.87% of the articles found were from these three years. Compared to 2018 with twenty-five articles, publications in 2020 and 2021 have nearly tripled in both years. Overall, it was observed that there was an increase in the number of AR studies by publication year.

When analyzed by citation (see Figure 2), no citations were reported in 2008 because there were no publications related to AR applications in science education that year. In addition, we found that the highest number of citations occurred in 2014, where 930 citations were recorded. This is closely followed by 2016 with 922 citations and 2009 with 863 citations. A total of 3 articles published in 2007 have been cited 667 times and 68 articles published in 2021 have been cited 77 times to date. Overall, 319 works have been cited 7532 times over time. This explains why there have been many studies on AR applications in the last decade.

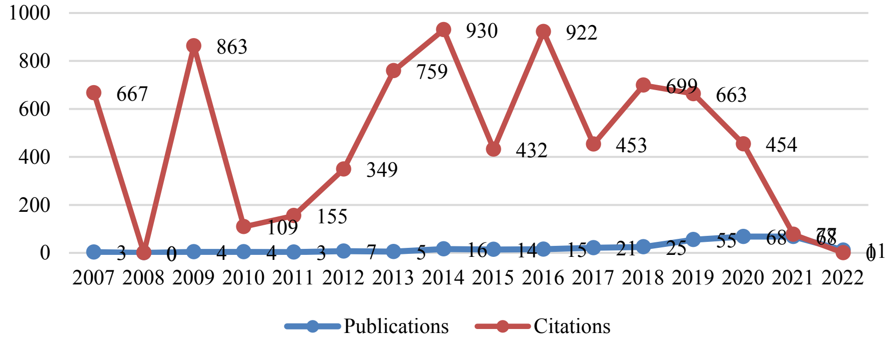

Fig. 2. Publications and citation trends in AR from 2007–2022

4.2 Author numbers

In order to answer the second research question, we examined the annual number of authors in the publication. Figure 3 depicts the change over time in the number of authors.

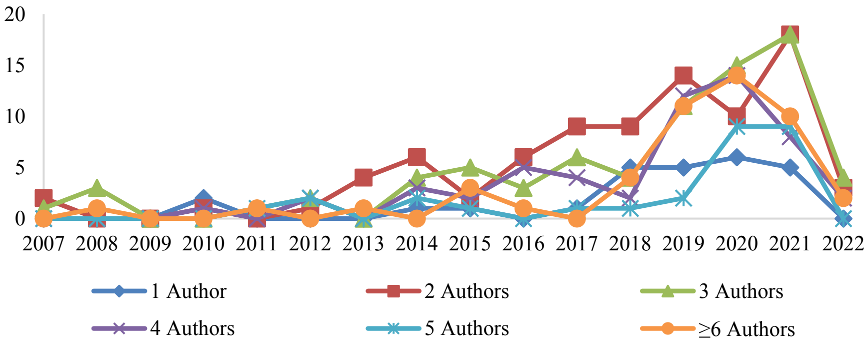

Fig. 3. Number of authors by year

As can be seen in Figure 3, there is also a noticeable increase in the number of collaborations over time. This reflects that there has been an increase in the number of publications on AR applications. With respect to the number of authors, it is worthy to note that only 26 single-author articles were published during this period. In addition, 85 articles have 2 authors with a proportion of 26.65%. This finding indicates that two-author articles were commonly published in this field throughout the year. A total of 77 articles were written by 3 authors. Furthermore, the number of articles with 4 authors experienced a rapid increase between 2018 and 2020. It is important to note that more than half of publications (65.20%) were written by at least 3 authors.

4.3 Top countries in terms of the number of publications

Aiming to respond to the third research question, we summarized the top 15 countries with regard to scientific production (see Table 1).

Table 1. The number of publications by country

Country	Number of Articles	Percentage (%)
United States	57	17.87
Taiwan	39	12.66
Turkey	27	8.77
Malaysia	23	7.47
Indonesia	17	5.52
Germany	17	5.52
Spain	16	5.19
China	11	3.57
Cyprus	7	2.27
South Korea	7	2.27
Australia	6	1.95
United Kingdom	6	1.95
Greece	5	1.62
Chile	4	1.30
Finland	4	1.30
Japan	4	1.30
Mexico	4	1.30
Portugal	4	1.30
Thailand	4	1.30

Based on the analysis, most of the first authors of the studies came from the US (n = 57, 17.87%), Taiwan (n = 39, 12.66%), and Turkey (n = 27; 8.77%). North Carolina State University and the University of Wisconsin–Madison (USA), National Taiwan Normal University and National Taiwan University of Science and Technology (Taiwan), and Ataturk University and Near East University (Turkey) were the most influential institutions. Twenty-three articles (7.47%) came from Malaysia and seventeen (5.52%) from Indonesia. In addition, there were studies from Germany (n = 17; 5.52%), Spain (n = 16; 5.19%), and China (n = 11; 3.57%). Cyprus and South Korea each produced seven articles (2.27%). Meanwhile, Australia and the UK published six articles (1.95%) and Greece published five articles (1.62%). The remaining six countries each published four articles (1.30%). Out of the top 15 countries, 9 countries (e.g., Canada, India, Italy) contributed three articles, 8 countries (e.g., Brazil, Denmark, Hong Kong) contributed two, and 14 countries (e.g., Croatia, Brunei, Bulgaria) contributed one. Of the 50 countries contributing to the articles, the studies came predominantly from Asia (n = 117; 36.68%), Western Europe (n = 77; 24.14%), Northern America (n = 60; 18.81%), and Middle East (n = 36; 11.29%). Besides, there were 12 articles that studied AR in Eastern Europe (3.76%) which was slightly more than the 11 studies that took place in Latin America (3.45%). These six locations were followed by Pacific Region (n = 6; 1.88%).

4.4 The most productive journals

Scientific journals that publish applications of AR in science education are identified. In order to address the fourth research question, we summarized the top 15 common relevant sources of AR (see Table 2).

Table 2. Top 15 most productive journals

Journal	*N*	Publisher
Journal of Chemical Education	19	American Chemical Society
Computers and Education	11	Elsevier
Journal of Science Education and Technology	9	Springer
International Journal of Emerging Technologies in Learning	9	Kassel University Press
Interactive Learning Environments	9	Taylor and Francis
Biochemistry and Molecular Biology Education	8	Wiley-Blackwell
Education Sciences	7	MDPI
Journal of Educational Computing Research	6	SAGE
International Journal of Interactive Mobile Technologies	6	Kassel University Press
Educational Technology and Society	6	National Taiwan Normal University
Physics Education	5	IOP Publishing
Eurasia Journal of Mathematics, Science and Technology Education	5	Modestum
Educational Technology Research and Development	5	Springer
Applied Sciences (Switzerland)	5	MDPI
Computers in Human Behavior	5	Elsevier

It is observed that the Scopus database has accommodated 164 journals that publish articles related to AR applications in science education. When the findings are examined, the most productive journals were *Journal of Chemical Education* with 19 publications (5.96%), followed by *Computers and Education* with 11 publications (3.45%), and *Journal of Science Education and Technology, International Journal of Emerging Technologies in Learning,* and *Interactive Learning Environments* with 9 publications each (2.82%). It reflects that these journals frequently published documents on the subject. Also, our analysis indicates that there were fewer AR user studies published in *Physics Education, Eurasia Journal of Mathematics, Science and Technology Education, Educational Technology Research and Development, Applied Sciences (Switzerland),* and *Computers in Human Behavior* (5 documents each, 1.57%). In the remaining sources, 4 journals have 4 papers, 8 journals have 3 papers, 27 journals have 2 papers, and 110 journals have 1 paper. Among the top 15 most productive journals, a total of two journals each owned by Elsevier, Springer, Kassel University Press, and MDPI. In contrast, American Chemical Society, Taylor and Francis, Wiley-Blackwell, SAGE, National Taiwan Normal University, IOP Publishing, and Modestum owned one journal, respectively.

4.5 The most cited papers

In order to address the fifth research question, we visualized the most cited studies in the field of AR in science education (see Table 3).

Table 3. Top 10 most cited publications

Authors	Title	Year	Journal	Citations
Dunleavy M., Dede C., & Mitchell R.	Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning	2009	Journal of Science Education and Technology	638
Potkonjak V., Gardner M., Callaghan V., Mattila P., Guetl C., Petrović V. M., & Jovanović K.	Virtual laboratories for education in science, technology, and engineering: A review	2016	Computers and Education	339
Squire K. D. & Jan M.	Mad city mystery: Developing scientific argumentation skills with a place-based augmented reality game on handheld computers	2007	Journal of Science Education and Technology	300
Kamarainen A. M., Metcalf S., Grotzer T., Browne A., Mazzuca D., Tutwiler M. S., & Dede C.	EcoMOBILE: Integrating augmented reality and probeware with environmental education field trips	2013	Computers and Education	271
Squire K. & Klopfer E.	Augmented reality simulations on handheld computers	2007	Journal of the Learning Sciences	257
Wojciechowski R. & Cellary W.	Evaluation of learners' attitude toward learning in ARIES augmented reality environments	2013	Computers and Education	257
Ibáñez M. -B. & Delgado-Kloos C.	Augmented reality for STEM learning: A systematic review	2018	Computers and Education	250
Chiang T. H. C., Yang S. J. H., & Hwang G. -J.	An augmented reality-based mobile learning system to improve students' learning achievements and motivations in natural science inquiry activities	2014	Educational Technology and Society	244
Cai S., Wang X., & Chiang F. -K.	A case study of Augmented Reality simulation system application in a chemistry course	2014	Computers in Human Behavior	221
Akçayir M., Akçayir G., Pektaş H. M., Ocak M. A.	Augmented reality in science laboratories: The effects of augmented reality on university students' laboratory skills and attitudes toward science laboratories	2016	Computers in Human Behavior	216

According to Table 3, the most cited paper was written by Dunleavy, Dede, and Mitchell in 2009 [8], with a total of 638 citations and an average of 53.16 citations per year. It was followed by the work of Potkonjak and colleagues [32] with 339 citations within 5 years and Squire and Jan [33] with 300 citations. Specifically, this article focused on how middle and high school teachers and students understand the ways in which participating in an AR simulation aids or hinders the teaching and learning process. The second most cited article in this area was Potkonjak et al. [32]. This review article aimed to look at new technologies that can overcome some of the potential difficulties in the teaching of science, technology, and engineering. Interestingly, the document published by Ibáñez and Delgado-Kloos [34] was cited 250 times within less than 3 years. This review article overviewed the use of AR technology to support student learning in science, technology, engineering, and mathematics (STEM)-related subjects. Without a doubt, STEM education has come to be the concern of researchers and educators around the world recently [35]. The other valuable publications in this area were Kamarainen et al. [36], Squire and Klopfer [37], Wojciechowski and Cellary [38], Chiang et al. [12], Cai et al. [39], and Akçayir et al. [2]. When examined by country, data analysis informed that the top ten publications belonged to the US (n = 4), Serbia, Poland, Taiwan, Spain, China, and Turkey (1 article each).

4.6 The most preferred research methods

The latest research questions are visualized in Figure 4. Figure 4 presents the change over time in the research method by year.

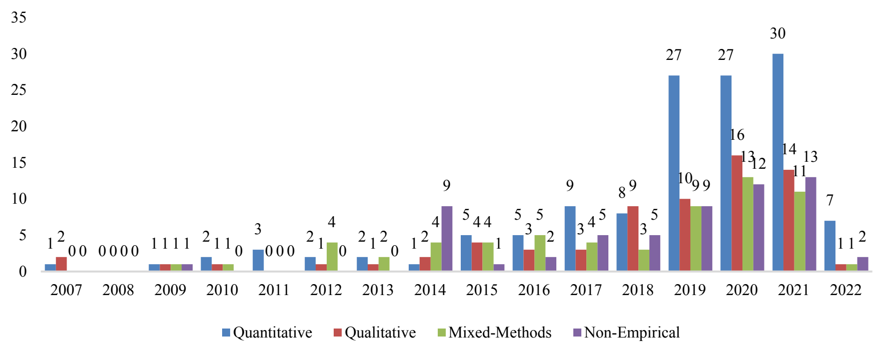

Fig. 4. Change in research method by year

When the research methods used in reviewed studies were examined, of the 319 studies, the most popular method used was quantitative (n = 130; 40.75%). The second most popular method was mixed methods (n = 68; 21.32%). Then, 19.44% of the articles adopted a qualitative approach (n = 62) and 18.50% preferred non-empirical research (n = 59). Figure 4 reflects the non-empirical approach gradually increased in the 2015-2021 period. However, the non-empirical approach still has the lowest ratio among all approaches. In 2019, the most widely employed research method in selected documents was quantitative design. Since 2020, the number of articles using qualitative or mixed methods started to decrease, while the number of articles using the quantitative method increased. In relation to the distribution of research methods over the years, quantitative design has been used throughout [6][35].

5 Discussions and implications

Within this section, we provided the research status and the development trend of future AR research from the perspective of academic research. When analyzed by the chronological evolution of research, the number of research literature shows a considerable growth tendency between 2007 and 2022. The current findings are in line with previous evidence [20][22][40]. For example, Akçayır and Akçayır [41] conducted a systematic review of the literature on AR used in educational settings from 2007 to 2015 and found an increase in the number of AR studies during the last four years. In a bibliometric study, Karakus et al. [42] also identified 437 publications related to AR in education between 1999 and 2018 and reported that the number of publications increased gradually after 2011 with a peak in 2017. Thus, the current review enriched the existing literature. A possible reason for increasing outputs during this period is the widespread use of AR through mobile devices. Nowadays, learning through mobile AR is becoming increasingly popular because of the small form of mobile devices and their ability to allow students to move freely while studying [43]. As an ideal platform for AR applications, previous evidence also claimed that mobile devices are very cost-effective and easy to use and offer a high level of social interactivity and independent operability [44]–[46]. Recently, Statistia [47] also released an increase in the number of mobile devices worldwide between 2020 and 2025. This systematic review implied that AR research has improved significantly over the years, fueled by the interest and attention of AR academics. Taking this trend into account, we predict that research interest in this area will continue intensely in 2022 and beyond.

With regard to author numbers, two-author papers accounted for almost a third of publications. In fact, the majority of publications were written by at least three authors. The result demonstrates that AR has attracted the attention of researchers and the research community as technological advances offer convenience for teachers and students in teaching and learning science. Given this pattern, it is likely that this research trend will continue in the coming year. In addition, this topic will be more interesting in the future as the number of research collaborations increases. The current findings are also supported by a study conducted by Dey et al. [48]. They systematically reviewed 10 years of the most influential AR user studies between 2005 and 2014 and reported that the average number of authors for each paper was 3.24. In a similar way, Tezer et al. [20] analyzed studies in AR applications published between 2001 and 2019 using meta-analysis methods. Of the 1008 articles, they concluded that a quarter of the publications (25.8%) had 2 authors and nearly 60% of the publications had at least 3 authors. This indicates that these papers are the result of collaborative research among researchers. Abramo and D'Angelo [49] claimed that articles written by more than one author have the potential to increase their visibility and impact. Thus, the current systematic review suggested that cross-country and cross-cultural research collaborations should be enhanced to play an important role in optimizing AR studies and dissemination in the future.

In relation to the prolific countries, the US outnumbers all the other countries with respect to the number of publications. Taiwan and Turkey are also among the top 15 countries whose contribution to the AR field has an essential influence. These three countries played a key role and account for more than a third of the total outputs of AR technology in science education. Unfortunately, there were no studies from African countries. Thus, there was a gap in the growth of publications among countries. It implies that more research from different countries is definitely needed. In this context, Avila-Garzon et al. [50] also reported that the US and Taiwan were in the top three productive countries in AR publications between 1995 and 2020. The findings are similar to those of the study conducted by Altinpulluk [22] and Buchner et al. [40]. This is a natural result of the long-term investments made by these countries in technology and education. When analyzed by region, Asian countries have the highest number of publications. This result is consistent with the findings of Altinpulluk [22] and Hedberg et al. [43], which noted that Asia is more dominant than Europe and America in terms of publication volume. We predict that countries that invest more in technology will benefit in a number of ways, particularly in education. As revealed by Pathania et al. [51], AR is an interactive technology that will bring massive changes to science education by providing a better and more effective environment. Therefore, the results of this review can stimulate science educators and other fields around the world to adopt AR technology in their teaching and learning.

In terms of the most productive journals, *Journal of Chemical Education* and *Computers and Education* topped the rankings. They were the most prolific journals on the use of technology in science education between 2007 and 2022. The results corroborate the findings of a study conducted by Karakus et al. [42]. The scope of these top journals indicates that the AR concept is widely studied in the field of science education during this period. The results of the analysis suggest that technology-related journals are dominant in AR publications. As the most productive resource in this review, *Journal of Chemical Education* published the most articles on AR. Founded in 1924, this journal has published numerous works on the applications of technology (e.g., software, media) to support the teaching and learning of chemistry at various levels of education. In addition, *Computers and Education*, founded in 1976, is highly committed to publishing papers focusing on the use of digital technology to improve education in general. Moreover, these two prestigious journals published peer-reviewed articles more than 12 times per year. This is a possible reason why these leading journals dominated research trends and were superior to other academic journals.

Regarding the most influential papers, the work of Dunleavy, Dede, and Mitchell [8], published in 2009, stands out as the most cited paper among the reviewed documents. This suggests that Dunleavy and his colleagues authored the most-cited studies in the field. As we know, Dunleavy is probably the leading author on AR in the literature. This result is in line with the findings of Avila-Garzon et al. [50], who noted that Matt Dunleavy is among the most cited authors in the field of AR in education over the past 25 years. Of the top 10 papers reviewed, most were from the US. It can be concluded that researchers from the US have made a significant contribution to this topic.

Surprisingly, the manuscript of Ibáñez and Delgado-Kloos [34] from Spain, which tends to be new in terms of year of publication, is ranked seventh in terms of total citations based on our dataset. This implies that this work has a major impact on AR applications in science education. In sum, researchers from developed countries have made valuable contributions to AR studies in science education. These researchers have significantly promoted the field and demonstrated consistency by contributing to the body of research in this area.

With regard to the distribution of research methods, the use of quantitative designs increased in recent years, especially between 2014 and 2021. This suggests that quantitative research methods are used more frequently than other research methods. The finding obtained in this review is supported by the literature. For instance, Arici et al. [19] conducted a bibliometric analysis of 147 articles related to the use of AR in science education in the period 2013-2018 from the WoS database. They reported that 81% of the documents employed quantitative design and only 6% preferred review or meta-analysis research. This is confirmed by Buchner et al. [40], who stressed that quantitative approaches are preferably employed in the period 2007-2019.

In the context of educational technology, quantitative studies generally evaluate the success of intervention when applied to a group of students in a particular setting. A possible reason why quantitative methods are often adopted may be related to the fact that the potential of AR technology in science education is well documented. For example, using AR has a positive influence on enthusiasm [6], academic achievement and spatial intelligence [7], STEM interest [35], and attitudes [5]. This implies that there are numerous research studies in the literature that investigate the effect of AR applications on student learning quantitatively. Another reason why quantitative designs are mostly employed in educational AR studies may be related to the familiarity of the scholars and researchers with quantitative methods and the wide acceptance of quantitative approaches than others [4]–[6]. This explains why there is a lot of research on AR technology adopting a quantitative approach. Therefore, the widespread use of quantitative designs is not surprising. Accordingly, there is an urgent need for more qualitative, mixed, and non-empirical studies in the future to bridge this gap. This literature review will serve as a reference for current and future researchers, policymakers, and practitioners involved in science education.

6 Conclusions

The current review presented a comprehensive view of the previous studies and offered some possible directions for researchers for further AR studies. A total of 319 papers were evaluated, encompassing annual scientific outputs, number of authors, most productive countries, most prolific journals, most cited articles, and most preferred research methods. It was found that the number of articles on AR applications in science education is increasing rapidly, and the field is gaining momentum. The peak is in 2020 and 2021. In terms of the number of authors, articles with two authors predominate in AR studies. Regarding the most productive countries, the United States, Taiwan, and Turkey are the three leading countries in publications on AR in the field of science education. In relation to the most productive journals, *Journal of Chemical Education, Computers and Education, Journal of Science Education and Technology, International Journal of Emerging Technologies in Learning,* and *Interactive Learning Environments* are among the most important journals publishing documents on AR in science education. It is well known that the authors with the most cited papers in the field of AR are Matt Dunleavy, Chris Dede, and Rebecca Mitchell with 638 citations, followed by Veljko Potkonjak and colleagues with a total of 339 citations and Kurt Squire and Mingfong Jan with 300 citations. From a methodological perspective, quantitative methods are the most frequently used but there have been only a limited number of non-empirical studies in the last 15 years. Therefore, it can be said that the results of the current review are important to guide future studies in this area and can be used as a reference for all stakeholders.

7 Limitations

This work has shed light on the status and trends of AR literature in science education. However, the current review is limited to documents published in the Scopus database; thus, the results of the current study may not represent the trends and developments of AR applications in science education. We recommend searching for relevant articles from other databases, such as WoS, ERIC, Google Scholar, and ProQuest in order to generate more representative data. Then, only articles published from the year 2007 onward and in English were included in this study; consequently, the literature search process may not identify all of the published articles over time. Since we only involved peer-reviewed journal articles, future researchers need to analyze conference papers, editorials, books, book chapters, theses, and dissertations. In addition, future studies may be able to combine bibliometrics and meta-analysis to present the findings as comprehensively as possible.

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