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Nguyen Mau Duc
Hanoi National University of Education, Viet Nam

Nguyen Vinh Quang
Hanoi National University of Education, Viet Nam

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Application of Augmented Reality in Chemistry Education: A Systemic Review Based on Bibliometric Analysis from 2002 to 2023

Nguyen Mau Duc, Nguyen Vinh Quang

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Abstract

This extensive bibliometric analysis examines Augmented Reality (AR) adoption and its effects on chemistry education from 2002 to 2023. AR's interaction, three-dimensional visualizations of molecular structures and reactions prove as a promising method for chemical concepts that are ever-increasingly sophisticated and for educational methods that tend to be less on repetition and more engagement. AR, by supplementing digital elements into the real world, enhances the visualization of more abstract chemical principles. VOSviewer and Biblioshiny were implemented for the visualization and analysis of Scopus database scholarly articles, conference proceedings, and educational case studies. Using this approach, relevant trends, themes, and the development of AR applications in chemistry education have been revealed. It is, therefore, obvious that the integration of AR in chemistry curricula has increased by far since the comprehension and student engagement in chemistry improved. AR applications improved spatial reasoning, which helps students understand molecular geometries and chemical reactions. This analysis shows that AR can be used for augmented textbooks and immersive lab simulations, demonstrating its educational flexibility. AR is a major step toward interactive and effective chemistry literacy. The study highlights AR in chemistry education and addresses emerging issues that will advance this dynamic field.

Introduction

Chemical education has traditionally used physical models, especially when it comes to helping students see molecules and comprehend chemical ideas (Chiu et al., 2021). The three-dimensional arrangement of atoms and bonds in molecules is typically represented using ball-and-stick models in traditional approaches (Serezhkin & Savchenkov, 2020). But as technology has developed, augmented reality (AR) has become a viable substitute for conventional physical models in chemistry education. AR is a technology that uses real-world camera images and virtual objects placed at specific points, simultaneously providing for interactions and interpretations through the resulting programs. In an AR application, the real environment is not directly encroached upon; it is an interaction between the real world and virtual objects (Arici et al., 2019). In recent years, augmented reality (AR) has significantly impacted the scientific and industrial fields due to its potential for deploying new content and affecting user perceptions (Hincapie et al., 2021). AR tools have been recognized for their potential to visualize complex scientific concepts, thereby increasing students' curiosity and understanding of various scientific disciplines (Lampropoulos et al., 2022).

Augmented reality (AR) has emerged as a promising technology in the field of education, particularly in the domain of chemistry education. The use of AR in chemistry education has been identified as a means to support educational and research activities, offering dynamic visual artifacts that foster the visualization capabilities of chemistry students. (Merino et al., 2022)The utilization of AR in teaching spatial relationships and chemical-reaction problem-solving skills has been highlighted as an effective approach for enhancing the learning experience of students (Singhal et al., 2012). The integration of AR in educational settings has garnered significant attention due to its potential to enhance learning experiences and facilitate a deeper understanding of complex chemical concepts (Нечипуренко et al., 2018). Furthermore, the application of AR technologies has been recognized as having great potential in education, with positive aspects confirmed by experiments in higher education institutions (Iatsyshyn et al., 2020).

The potential of AR in online education has also been explored, emphasizing its prospects for enhancing online learning experiences across various disciplines (Tiwari et al., 2023). The role of emerging trends, including AR and virtual reality (VR), has been acknowledged as vital in transforming educational practices, particularly in practical laboratory exercises (Mobo, 2021). The development of AR practicum modules has been investigated as a means to promote independent learning and adapt to the evolving needs of educational practices (Ratnawati et al., 2022). The use of mobile AR has been explored to gain insights into its effectiveness in assisting chemical education, particularly in enhancing students' perception and understanding of chemical concepts (Yang et al., 2018). Moreover, the emergence of AR technologies has led to the development of innovative solutions for chemistry learning, integrating principles of AR and gamification to create interactive educational systems (Lokodi & Ștefãnuț, 2021). Augmented reality (AR) has emerged as a promising technology with the potential to revolutionize the field of chemistry education (Shaukat, 2023). AR technology has the potential to create immersive and interactive learning environments, allowing students to visualize abstract chemical concepts in a more tangible way (Shaukat, 2023). By overlaying digital information onto real-world objects, AR can help students understand molecular structures, chemical reactions, and laboratory procedures with greater clarity. Additionally, AR can provide personalized learning experiences by adapting to individual student needs and offering real-time feedback, fostering a more engaging and effective learning process (Papanastasiou et al., 2018). The integration of AR in chemistry education has been the subject of extensive research and development, with a focus on enhancing visualization, facilitating flipped and gamified learning, usability testing, and supporting laboratory learning (Aw et al., 2020; Fombona-Pascual et al., 2022).

The application of AR technology in chemistry education has shown significant potential for improving students' understanding of complex 3D molecular structures and fostering their visualization capacities (Merino et al., 2022; Ya Midak et al., 2022). Furthermore, AR has been identified as a valuable tool for promoting guided discovery learning and enhancing students' engagement and interest in chemistry education (Abd Majid & Abd Majid, 2018;

Adnan et al., 2022). The use of AR in chemistry education has also been explored in the context of supporting STEM learning, where it has been found to be effective in promoting a deeper understanding of chemical concepts and improving students' learning experiences (Nussipova et al., 2019). Additionally, the development of web-based AR platforms, such as MoleculARweb, has expanded the accessibility of AR technology for chemistry and structural biology education, making it available across various devices. The potential of AR to transform 2D molecular representations into interactive 3D structures has been recognized, offering a novel approach to teaching spatial reasoning skills to chemistry students. Moreover, the integration of markerless AR technology has been proposed as a conceptual model for interactive educational and methodical complexes, further highlighting the diverse applications of AR in modern education (Christopoulos & Pellas, 2020). As such, the exploration of AR in chemistry education presents an exciting opportunity to enhance the learning experience and improve students' grasp of complex chemical concepts (Chiang et al., 2022). This introduction aims to provide an overview of the current state of AR in chemistry education, highlighting its potential to transform the teaching and learning process in this field.

In light of these developments, this study will investigate the trend of using Augmented Reality in chemistry education. The bibliometric mapping analysis added to the amount of variables in addition to the content analysis. A broad evaluation was offered after a review of all articles published from 2002 to 2023 regarding the use of AR in chemistry education was conducted. By analyzing methodological research trends year after year and the bibliometric mapping analysis results of all associated published publications, the purpose of this study was to identify any necessary or missing components. It is believed that by means of this thorough content and bibliometric mapping analysis, our findings would offer a significant addition to scholars looking into AR applications in science education. The objective is that this work will demonstrate a useful resource for researchers in this field in the future. The research questions set out in this study, all of which relate to entries in the 'Scopus' online literature source, are listed below:

1. Which keywords are most frequently used in papers about augmented reality (AR) in chemistry education?
2. What are the general characteristics of scientific research and publications?
3. In papers on the use of augmented reality (AR) in chemistry education, who are the most cited (citation and co-citation) authors?
4. In papers on the use of augmented reality (AR) in chemistry education, which are the most cited (citation and co-citation) journals publishing articles?

Methodology

Preliminary analysis of published research demonstrates that, in recent years, there has been a tendency toward diversity in the field of study on the application of augmented reality in chemistry education. Researchers can provide a systematic and reasonable literature basis for further in-depth research by using software to conduct a bibliometric analysis of the existing literature. This will assist researchers describe the research status and research trends in the application of Augmented Reality in chemistry education. Consequently, this study used the basic analysis function of the Scopus database to perform a descriptive statistical analysis of the literature and further, this study visualized and analyzed the literature using Biblioshiny and VOSViewer software in order to comprehensively synthesize the majority of existing literature.

Data Selection Process

In compliance with previous research protocols, this study used the Scopus database as database (Puspita & Shikur, 2023; Sankar, 2019; Truong Son & Thanh Hai, 2023). For citation analysis and search, Scopus is the most used information platform worldwide (Wakil, 2020). The procedure for choosing literature is as follows: The data was collected in December 20th, 2023. Originally, 263 document results were found using keywords in searching metadata: “TITLE-ABS-KEY ("augmented reality" AND chemistry AND (educat* OR teach* OR learn*)) AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar")). Data is also limited on document types: Articles, Conferences and Book Chapters. Lastly, carefully go over the abstracts and titles of the chosen papers, eliminating any that had nothing to do with the application of augmented reality in chemical education. The articles must meet certain requirements, such as having specific data on "Augmented Reality" and "chemistry education" in the title, keywords, or abstract. Additionally, the articles must be read in their entirety if these sections do not provide the necessary information. In the end, this study produced 231 example articles. The text is exported as a rudimentary sample for further examination. Figure 1 illustrates the selection results of each step.

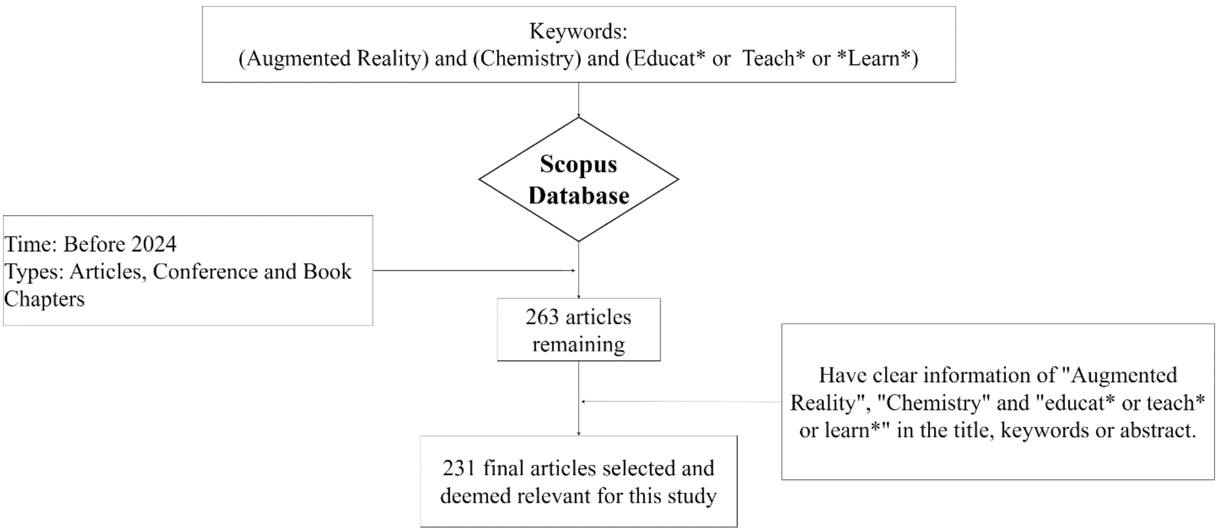

Figure 1. Literature Screening Flowchart

Data Analysis

This bibliometric analysis explores growth and emergent trends in Augmented Reality (AR) for chemistry education over 2002 to 2023. It identifies publications constituting a basis for comprehensive review of the field, establishing work breadth undertaken to date and stage of evolution achieved. Key to this study, is an identification of patterns, shifts in focus and seminal contribution that have shaped the integration of AR in chemistry education. Analysis should outline the general features of the collected works in order to provide the contextual backdrop for more detailed examination. A review of the trend in publication chronologically in this regard demonstrates the growth trajectory of the research field highlighting the way increasing research interest and academic emphasis in AR for chemistry education have transformed.

Central to this study will apply the advanced keyword analysis as a technique that underscores the dominant and emerging themes of research within the field. As it analyzes the frequency as well as the context of keywords, it provides a comprehensive picture of the thematic landscape showing the ascendance of certain concepts and new areas of research. This is through the use of sophisticated bibliometric tools that include Scopus, VOSviewer as well as Biblioshiny to fully manage, visualize, and appropriately interpret big as well as complex datasets. Notably, these bibliometric tools play a critical role in structuring meaning from bulky datasets. Furthermore, from the co-occurrence and co-citation, an analysis of interconnectivity between members of the research community within defined key clusters of research and influential works that signified major themes or methodological convergence of interest within the studies will be presented. This not only throws light on the insider intellectual backbone of AR in chemistry education but it also points towards the crucial moments where new ideas or technologies have spurred significant shifts in the research drifts.

Results

The published document results in Table 1 represent the various attributes of a published document in Scopus before 2024 related to the application of Augmented Reality (AR) in chemistry education. A notable point is the distribution of document types revealed that they included 113 articles and 118 conference papers resulting in roughly equal contributions from both published formal research as well as conference presentations. This points out to a dynamic field where circulating information is attained not only through traditional academic publications and research journals but also in professional meetings. The most impressive figure, however, lies at the annual growth rate of 17.58%, which greatly reflects an exponential upsurge in interest in AR in relation to chemistry education. This growth rate points to the ever-increasing recognition of AR as an important tool in educational contexts.

Another explicit aspect is the average age of documents is equal to 4.7 years. This quite young age reflects its novelty and never-ending development in that particular area of research. In addition, it also shows that this field of study is relatively young and dynamic because discoveries and technologies are emerging fast. The mean citations per document from a cumulative total of 11.99 present a reasonable level of involvement with the academic impact as a contribution in the given area of study. This number is an average of all the time that these documents were cited with the other works, inevitably proving research in this field is well accepted and it leaves a great impact on future studies. The number of references (6949) and keywords (1061 Keywords Plus and 559 Author's keywords) is so vast as to draw attention to the comprehensiveness of research in this domain. These figures represent rich and diverse landscapes of research with a range of varied topics being explored under the umbrella of AR in chemistry education. Last, the human component in this field of investigation is shown through the number of authors (734) and also the presence of international collaborations (12.99% of the documents have international co-authors). This points to the collaborative and global effort in researching AR applications in chemistry education reflecting the universal relevance and interest in this innovative educational technology.

Overall, the figures from Table 1 give a collective impression of lively dynamism and a fast-growing international research community. The data tend to hint that chemistry education is one domain where the use of AR applications is not only gaining ground but also being entrenched increasingly in academic-impact work.

Table 1. Document Attributes on AR in Chemistry Education

Attribute	Number or Magnitude
Sources	132
Documents	231
Articles	113
Conference papers	118
Annual growth rate	17.58%
Average age of documents	4.7
Mean citations per document	11.99
References	6949
Keywords Plus (ID)	1061
Author’s keywords (DE)	559
Authors	734
Single authors (with no co-author)	12
Single-authors per document	15
International co-authors	12.99

Turning to Figure 2, presenting the annual numbers of publications on a topic of applying Augmented Reality (AR) in chemistry education for the period from 2012 to an extrapolated number for 2023, one may observe a trend describing the increment in research activity with years. The beginning's publications count is low and fairly constant during 2012-2014, with a yearly average of about 5.7 publications. This period most probably characterizes the nascent stage of AR application in chemistry education, where the technology was emerging and its educational potential was just starting to get utilized. A major inflection point came in 2015 wherein publications more than doubled to 11, indicating that the value of chemically-oriented education was rapidly growing. The number fell to an average rate of 4.5 in 2016-2017, which might represent a consolidation phase with researchers assessing the impact and effectiveness of AR technologies introduced during the previous surge.

There from 2018, the line graph makes way into an advancing trend with an uptrend moving up, peaking at 15 publications. The number of publications then shows a growth spurt as it shoots up to 48 in 2021. This sudden increase could maybe be due to the advancements of AR's technologies maturing or external factors like an increase in funding for educational technologies and changes in how education is taking place. Significantly, a plateau emerges in 2022 from the peak of 36 publications in 2021 that may imply on a drop in research output before leveling off after the previous year's high.Attention needs to be paid for the slight decline to 30 publications in 2023. Such a decline could represent one of several factors: a settling back after an exceptional period of growth, the completion of many large research efforts, or perhaps an approaching state of theoretical or practical saturation from which some of the initial basic concepts underlying the field have been forgotten. Otherwise, it may well indicate the beginning of another phase towards quality-based and in-depth research rather than quantity as the domain comes of age.

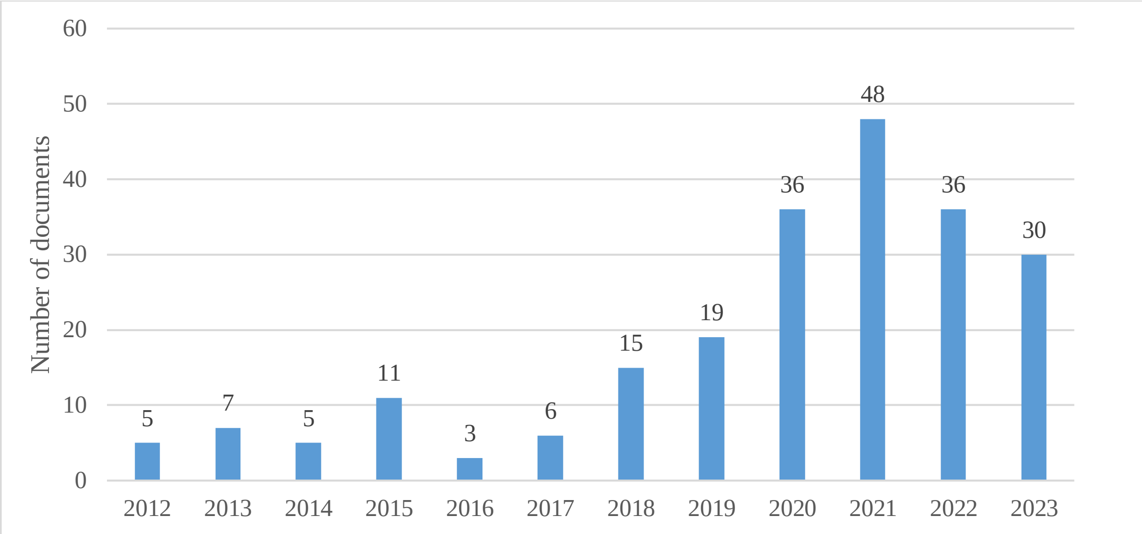

Figure 2. AR in Chemistry Education Publications

Summarily, data from Figure 2 shows that the field is booming and widening with intermittent periods of stability. This overall upward trend in publications attests to an increasing importance and recognition of AR in chemistry education perhaps suggesting that AR is becoming an established area for academic inquiry and educational practice. The peak in 2021 followed by a plateau and a slight decrease in 2023 suggests the dynamics of the research in this area pointing, that interest is not declining nor dying out but rather moves from one aspect to another over time and possibly toward more refined and focused questions on the application of AR in chemistry education.

Table 2. Top 10 Countries by AR Contributions to Chemistry Education

Rank	Country or territory	Total publications	Share in total (%)	Total citations	Citation rank	Share in total citations (%)	Total citations/total publications
1	United States	33	14.3	459	1	13.1	13.9
2	Indonesia	26	11.3	138	8	3.9	5.3
3	Taiwan	18	7.8	184	6	5.2	10.2
4	Germany	17	7.4	131	9	3.7	7.7
5	China	12	5.2	421	2	12.0	35.1
6	Switzerland	11	4.8	227	5	6.5	20.6
7	Portugal	10	4.3	24	18	0.7	2.4
8	Malaysia	9	3.9	236	4	6.7	26.2
9	Spain	9	3.9	56	14	1.6	6.2
10	United Kingdom	9	3.9	371	3	10.6	41.2

Overall, 51 of the 235 papers come from authors affiliated with one of 234 different countries or territories. Table 2 shows that weight is placed on the number of publications released by the top 10 writers. With 33 publications, representing 14.3% of all publications, the United States topped the list. Indonesia is on second place (26 publications with 11.3%), Taiwan is third (18 publications with 7.8%), the top 5 is China (12 publications with 5.2%) and number 8 is Malaysia (9 publications with 3.9%). In such a way, four Asian countries are introduced here as well as it could be seen in the table in the initial sources. Besides, the USA has also shown a leading rate of citing (459, or 13.1%, which is a mean increase from 11.2 to 13.9 citations per document), followed by China (421, or 12.0% with a mean increase from 29.4 to 35.1 citations per document).

Based on the previous explanation related to the international collaboration network, it is analyzed as a network of international collaboration for research application of AR in chemistry education, which can be seen in Figure 3. It can be seen that there are twenty-five nations that join the network, and these nations are divided into five main groups, or clusters: (1) The United States of America, Argentina, Iran, Chile, and Colombia; (2) Germany, Switzerland, Netherlands, Sweden, Belgium, and Palestine; (3) Portugal, the United Kingdom, France, and Thailand; (4) China, Singapore, Australia, Ecuador, and New Zealand; and (5) Spain, Mexico, Pakistan, and Slovakia.

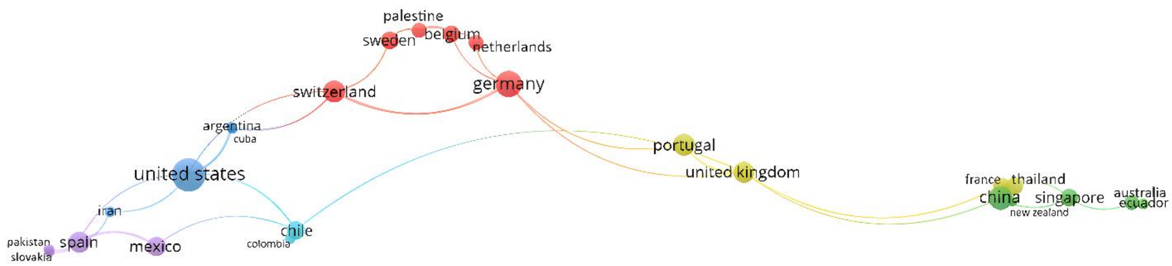

Figure 3. Network of Countries Researching AR in Chemistry Education

Note: The size of the circle is proportional to the number of research publications from that country (Table 2).

The network of the countries working on research pertaining to the application of AR technology for the purpose of chemistry education, as shown in Table 3. Together with the correlation statistics, graphical representation makes it possible to infer various aspects related to the global phenomenon and collaborative countries involved in this subject domain. The circles' size in the network map is proportional to the number of research publications and provides a clear visual of which countries of the most research publications. The larger circles in the countries represent the greater amount of research output, which shows that these countries dominate or are engaged with a heavy concentration on AR applications in chemistry education. Most importantly, the interconnections among countries signify that this study comprises a collaborative initiative. The countries with stronger or more numerous lines between their borders would indicate an intensification of collaborative efforts, pointing towards a trend of international partnership in advancing AR technology for education.

In other words, Figure 3 represents both the leading countries in AR application in chemistry education as well as those emphasizing inter-countries collaboration in this field. It demonstrates general interest in the new technology and its integration into educational practices.

Table 3. Top 8 Sources Ranking

Rank	Source	Type	Total publications	Total citations	CiteScore 2022
1	Journal of Chemical Education	Journal	25	450	5.2
2	Lecture Notes in Computer Science	Book Series	11	63	2.2
3	AIP Conference Proceedings	Conference Proceedings	10	34	0.7
4	Journal of Physics: Conference Series	Conference Proceedings	9	51	1.0
5	ACM International Conference Proceeding Series	Conference Proceedings	8	24	1.1
6	CEUR Workshop Proceedings	Conference Proceedings	7	145	1.1
7	Biochemistry and Molecular Biology EEducation	Journal	6	121	2.3
8	International Journal of Interactive Mobile Technologies	Journal	4	15	4.2

When looking at the Table 3 that analyzes the top eight sources in terms of publications about the application of Augmented Reality (AR) in chemistry education, there are various trends and implications presented to the field. The leading niche is the "Journal of Chemical Education", with 25 publications and 450 citations indicative of strong interest and impact in this niche. The high relevance and quality of contributions are attested to by its high CiteScore at 5.2. This implies that since the journal plays a leading role in integrating AR into teaching chemistry, it may further present various perspectives and usages of this AR technology. 'Lecture Notes in Computer Science' and 'AIP Conference Proceedings,' on the other hand, published fewer articles (11 and 10). It may be the indication of a more specialized or emerging interest in the use of AR applications within this forum, as suggested by the lower citation numbers (63 and 34) and CiteScores (2.2 and 0.7) for this journal and transactions. This may suggest that AR in chemistry education is indeed an area yet to be fully emerged among larger computer science and physics communities too. The conference proceedings included a "Journal of Physics: Conference Series" that had a very considerable showing as well as the "ACM International Conference Proceeding series," and it also followed suite. Maybe it was because of the dynamic nature of conference presentations, in which they capture what is fresher and most experimental in its application. The fact that "Biochemistry and Molecular Biology Education" and "International Journal of Interactive Mobile Technologies" belong to the list underlines the interdisciplinary or multidisciplinary character of the AR applications in education, bridging on one hand between chemistry and biology, and on the other, through application-mobility technology.

In general, this data just illustrates an increased interest in and various approaches towards AR application in chemistry education. This indicates the tendency for a more interactive technology-based way of providing education and helps to identify the main sources contributing to this field. This diversity in sources and types of publications thus also indicates that this field is dynamic and developing so that further innovative applications and research may be envisaged.

Table 4. Top 9 Authors Ranked Publications

Rank	Author	Affiliation	Total publications	Total citations	Total citations/total publications
1	Abriata, L.A.	École Polytechnique Fédérale de Lausanne, Switzerland	6	65	10.8
2	Nisi, V.	University of Lisbon, Portugal	6	9	1.5
3	Huwer, J.	University of Konstanz, Germany	5	15	3.0
4	Klinker, G.	Technische Universität München, Germany	4	30	7.5
5	Maier, P.	Technische Universität München, Germany	4	30	7.5
6	Matsubara,Y.	Hiroshima City University, Japan	4	4	1.0
7	Nechypurenko, P.P.	Kryvyi Rih State Pedagogical University, Ukraine	4	139	34.75
8	Okamoto, M.	Hiroshima City University, Japan	4	4	1.0
9	Romão, T.	NOVA University Lisbon, Portugal	4	3	0.8

Table 4 provides an engaging cross-section of the top 9 authors in the domain, ordered by their publication output related to the use of Augmented Reality (AR) in chemistry education including affiliations, total publications, total citations, and average citations per publication. This data helps us to know the key players in this domain of research and gives an estimate of their work.

Abriata L.A. from École Polytechnique Fédérale de Lausanne in Switzerland tops the number of publications list at 6 in the table, thus contributing to its accumulated citations total of 65; which then drops to a mean average score of 10.8 citations per publication. These results of high citation rate per publication indicate not merely that the work of Abriata is prolific but also highly influential within the academic community suggesting their research contributions have been foundational in integrating AR technology into chemistry education. On the other hand, Nisi V. from the University of Lisbon, Portugal, has published 6 papers but with a relatively low citation count of 9, averaging 1.5 citations per publication. This discrepancy shows that the impact and citation of the research differ not only across fields and disciplines but also within them, maybe because of the topics researched, the novelty of the findings, or the applicability to education. An example of an outlier in terms of its citation impact is the work by Nechypurenko P.P. from Kryvyi Rih State Pedagogical University, Ukraine with 4 publications and with whopping total citations of 139. The average of that will be approximately 34.75 citations per publication. This indicates that this paper by Nechypurenko has deep resonation within the community and perhaps addressed pioneering methodologies, or insight into the application of AR in chemistry education.

The geographical diversity among top contributors is also enlightened in the table, revealing that they are from Switzerland, Portugal, Germany, Japan, and Ukraine, pointing out to a global scale as far as interest in AR applications in chemistry education is concerned. This diversity strengthens the universality of AR technology and its usage globally in improving the level of education in different cultures and institutions. In short, whereas Table 4 enlightens leading authors, it is both a glimpse of the academic landscape in chemistry education. It delineates the different effects of research contributions and highlights both the quantity and the quality it brought out on scholarly publications. The table provides an interesting microcosm of the field, showing international interest and opportunity for collaboration in using AR technologies to innovate and improve chemistry education.

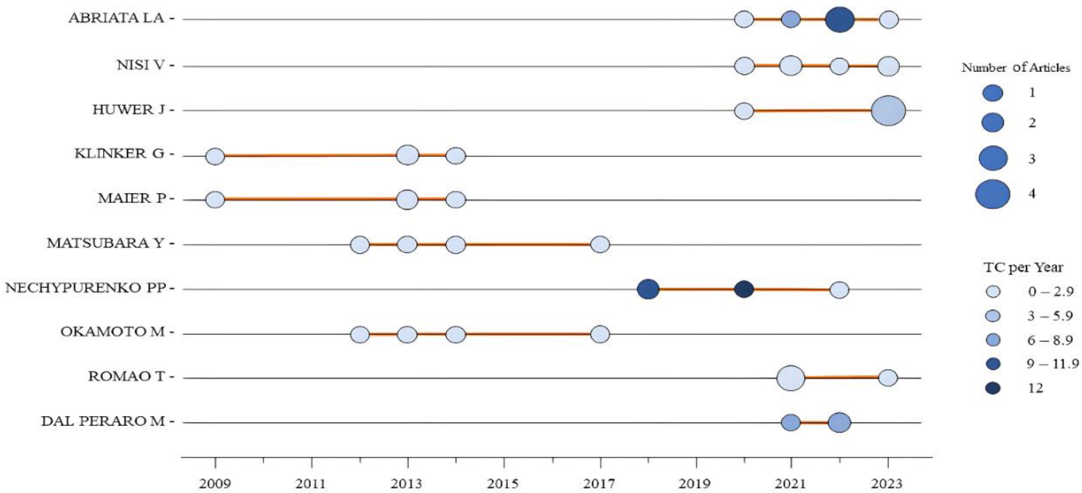

Figure 4. Top 10 Most Prolific Authors' Publication

Figure 4 illustrates the publication output of the leading authors in the field over a specified timeline. The visualization will likely use a timeline graph or bar chart in which for each author each year is drawn ticked to the height of that author's number of publications so user can see trends, productivity peaks and how does the research focus changed over time. Analysis of such a figure helps us not only learn who are the key contributors to this certain niche of educational technology but how that research output has developed thus indicating the development or maturation of the field and evolving interest towards AR applications in chemistry education.

The specific data points, while not visible in the textual description of Figure 4, would enable a deeper analysis. For example, if an author has indicated a certain remarkable increase in his publications after some years, this could be related to the influential developments of AR technology or to the important changes in educational theory, which justify the use of technology in learning settings. Moreover, a collective output of top authors can be indicative of the vibrancy in the field and the depth to which AR is engaging the interest of the academic community to engage AR in chemistry education. Further, this graph may also reveal collaboration trends between prolific authors if the date signifies simultaneous publication output peaks thus signifying collaboration projects or research initiatives. It also helps identify leading experts whose work could define the core themes and methodological approaches in the field.

Table 5. 10 Most Cited Papers

Rank	Title of the publication	Authors and year	Published in	Total citations	Citations per year
1	A case study of Augmented Reality simulation system application in a chemistry course	Cai, Wang, Chiang 2014	Computers in Human Behavior	310	28.18
2	A review of research on augmented reality in education: Advantages and applications	Saidin, Halim, Yahaya 2015	International Education Studies	177	17.70
3	A study of comparing the use of augmented reality and physical models in chemistry education	Chen 2006	Proceedings - VRCIA 2006: ACM International Conference on Virtual Reality Continuum and its Applications	114	6.00
4	Augmented Reality (AR) Technology on the Android Operating System in Chemistry Learning	Irwansyah, Yusuf, Farida, Ramdhani 2018	IOP Conference Series: Materials Science and Engineering	94	13.43
5	Augmented Chemistry: An interactive educational workbench	Fjeld, Voegtli 2002	Proceedings - International Symposium on Mixed and Augmented Reality, ISMAR 2002	78	3.39
6	Tangible user interface for chemistry education: Comparative evaluation and re-design	Fjeld, Fredriksson, Ejdestig 2007	Conference on Human Factors in Computing Systems - Proceedings	77	4.28
7	Use of augmented reality in chemistry education	Nechypurenko, Starova, Selivanova 2018	CEUR Workshop Proceedings	64	9.14
8	Development and implementation of educational resources in chemistry with elements of augmented reality	Nechypurenko, Stoliarenko, Starova, Selivanova 2018	CEUR Workshop Proceedings	60	12.00
9	Mobile Augmented Reality Assisted Chemical Education: Insights from Elements 4D	Yang, Mei, Yue 2018	Journal of Chemical Education	59	8.43
10	Using augmented reality to experiment with elements in a chemistry course	Chen, Liu 2020	Computers in Human Behavior	56	11.20

Table 5 analyzes the study that was produced in the report to provide more detailed insights into the perceived impact and reception of augmented reality (AR) applications in the context of chemistry education. This table is outlining the top 10 most cited papers demonstrating scientific contributions of AR in chemistry education, figuratively giving a sense to readers about which contribution has resonated most with the professional community.

Upfront is "A case study of Augmented Reality simulation system application in a chemistry course" by Cai Wang Chiang (2014) published in *Computers in Human Behavior*, gaining an incredible 310 citations to date and on average approximately 28.18 citations per year. This high citation rate underscores the impact of this paper and the relevance of its findings in the broader academic discourse on AR in education. This highlights the potential value of insights gained from this studys focus on AR simulations in a chemistry course to give them ideas about practical applications for AR technology as a way of improving students learning experiences and outcomes.

Closely following is "A review of research on augmented reality in education: Advantages and applications" by Saidin Halim Yahaya (2015), with 177 citations with an average citation per year at 17.70, and published in *International Education Studies*. The great number of citations that the majority of them received compared to other review papers on the topic indicates that this review paper is an important extensive survey of the benefits and uses of AR in education, and therefore can be taken as an indispensable reference body for researchers and educators who may be considering the adoption of the use of AR to guide and improve their teaching.

Indeed, the interdisciplinary nature of AR research in education is presented using the diversity of its publication venues - from high-impact journals like Computers in Human Behavior - to typical conference proceedings and specialized educational series. Moreover, the diversity of the 17 articles not only evidences a broad-based interest in AR's educational applications but also testifies that the contributions of AR to chemistry education are appreciated across the gamut of academic venues.

In sum, data from Table 5 reflects a growing academic consensus that AR holds value in enhancing chemistry education. These figures of the high count of citations for the publications are indicative of academic community recognition of the possibility potential of AR in revolutionizing educational methodologies, specifically making students understand complex chemical concepts through more accessible and interesting techniques.

In Figure 5, the network visualizes keywords with regard to their co-occurrence in papers on use of Augmented Reality (AR) technology for chemistry education. Such an association graph would be essential to understand thematic flow and emerging nodes of attention during research in this domain. The network picks the interrelatedness of different terms showing the density and centrality of some keywords which implies their importance in the subject area. This way analysts may be able to identify the core concept themes and emergent areas in AR applications to chemistry education. The more central keywords across the network of keyword connections and manifests probably represent a distinctively common keyword and represent more fundamental concepts making broader research domains. They could range from directly relevant AR technology ("augmented reality," "virtual reality") to pedagogical approaches ("interactive learning," "gamification") and even chemistry education topics ("molecular structures," "chemical reactions").

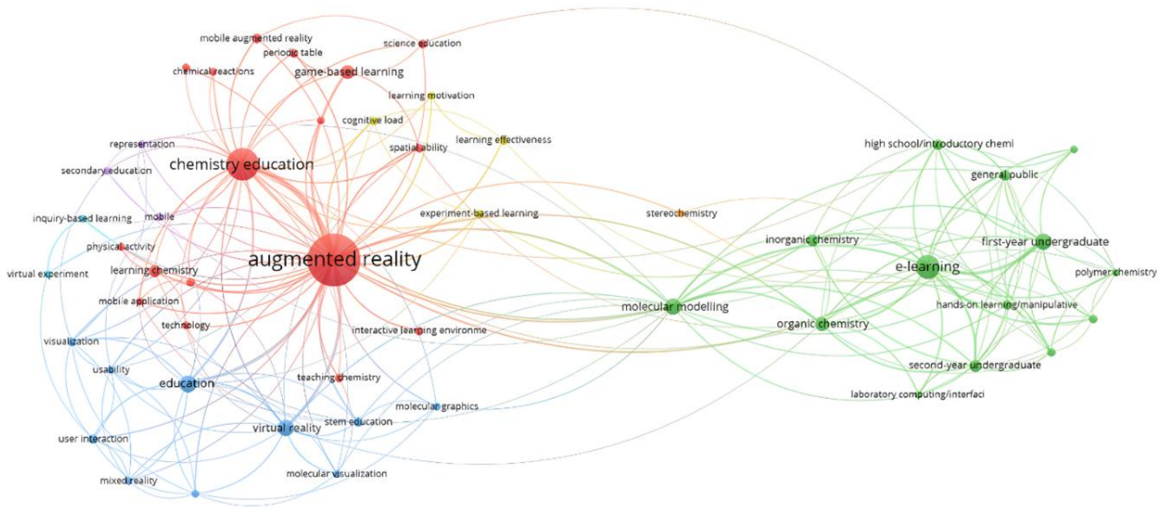

Figure 5. Network of Keywords

This may also be informative for the visual network in terms of its links to cognitive psychology (e.g., "cognitive load", "spatial understanding"), technology development (e.g., "user interface design", "haptic feedback"), and educational assessment (e.g., "learning outcomes", "student engagement") with regard to AR given its interdisciplinary context of application in education. Such diverse terms show varied impacts of AR technology on chemistry education from student engagement and understanding to curriculum designing and teaching strategies.

Overall, as a landscaping map of AR in chemistry education, Figure 5 works not only that but also like a tool to show gaps in the literature and possibilities for directions for future study in this research area. This is further highlighted through a network visualization that enriches and presents this research domain as complex and promising - hence worth furthering the investigation in and for interdisciplinary dialogue to be established in order to fulfill the promise of AR in enhancing chemistry education.

Discussion

Consistent with the reviewed literature, this research demonstrates how AR has been integrated into chemistry knowledge systems, emphasizing its effectiveness in improving students' understanding of refinement and elaborate concepts. AR applications in learning have been widely used, particularly in the illustration of molecular structures and mechanisms of chemical reactions to ensure a more profound and active learning process (Lewis, 2024). This made the success of AR stand apparent that reduced attrition with improved student comprehension and retention of information, making them attentive and motivated for the subject (Gargrish et al., 2022). However, there is also the need to appreciate the variation in the effectiveness of AR technologies across varying learners and learning contexts (Garzón et al., 2020).

The developments within the AR technology have serious ramifications on pedagogical methodologies within the learning structures intended for chemistry education (Garzón et al., 2020). The analysis indicates that the constructivist learning theories received several endorsements from researchers who showed that there has been a trend toward more interactive and engaging learning experiences (Lorimer Moseley et al., 2023). The new possibility provided by technology that allows AR solutions offers great prospects for enhancing the practicality of training because it allows students to handle and interact with chemical structures and processes within a virtual environment (Alzahrani, 2020). This will help in developing an overall learning process, that potentially bridges the gap between theoretical learning and its practical application (Iatsyshyn et al., 2020).

The bibliometric analysis identifies an increasing interest in the application of AR in chemistry education, with a remarkable increase of publications under research in this area for the last 20 years (Talan, 2021). Emerging trends include incorporating AR within collaborative learning and linking it with other technologies such as virtual reality (VR) and artificial intelligence (AI) (Scavarelli et al., 2020). The future of AR in chemistry may see more personalization of the learning experience and adaptive learning systems that cater to the individual learner, adapting automatically to the student's unique learning styles and needs.

This indicates that AR research in chemistry education is more global, translated beyond the country-specific and culture-specific (Tsui, 2022). Such diversity not only brings a value-based orientation but also lends different approaches to integrations within the sub-discipline enabling enrichment of the domain (Wang et al., 2021). Sharing the best practices of experience and research findings, as well as spreading the development of more effective and universally available educational AR tools, is of much importance in the context of cooperation (Huang et al., 2021).

One of the central research tides within the field of AR constitutes an issue of the impact that it has on students' motivation and engagement (Kaur et al., 2020). AR technologies have been found to improve student interest and engagement in learning making it more fun and interesting (Videnovik et al., 2020). Increased engagement, therefore, is associated with increased performance and a deeper conceptual understanding of chemistry (Petillion & McNeil, 2020). The use of AR in the chemistry classroom also comes with its own set of disadvantages (Sirakaya & Alsancak Sirakaya, 2020). Technical challenges, for instance, the need for compatible hardware and software may present a challenge (Alzahrani, 2020). Additionally, financial and infrastructural issues come into perspective, more so where less-resourceful education environments are involved (Mythiri & Karthika, 2023).

Conclusion

Augmented Reality (AR) integrated in chemistry education represents a huge step towards more interactive learning environments as well as very immersive also. The following comprehensive bibliometric analysis from 2002 to 2023 underscores the growing interest and varied applications of AR in enhancing students' understanding of complex chemical concepts. Abstract theoretical knowledge would through AR become tangible and students may visually interact with molecular structures and chemical reactions in ways that would not be possible with ordinary experiences. The findings illustrate the potential AR carries to advance educational outcomes by enhancing deeper engagement, and spatial ability, and fostering innovation.

The exponentially high growth of publications and research attention reveals that value has been noted for AR with regard to educational technology. Nevertheless, a lack of balance concerning AR applications in the effectiveness in different learning contexts calls for more research on its pedagogical integration. Future studies will aim to identify best practices for the implementation of AR, explore the impacts of AR on learning outcomes in diverse student populations as well as address challenges such as technological accessibility and pedagogical alignment.

The universality and potential of AR technologies resonate with the interdisciplinary nature as well as international collaboration that underlies research in chemistry education. As AR evolves in sophistication and accessibility, its role in education is expected to grow, offering new chances for personalized and adaptive learning experiences. In harnessing the full potential of AR in enhancing the quality of chemistry education, ongoing research and innovation are paved out as key, thus qualifying it as a critical area in the future development of educational technology.

Recommendations

In general, the analysis made on AR applications in the teaching process and learning underlines a high potential for a positive impact on the learning environment but also on learning how to understand concepts and increasing the level of student involvement. However, to grasp the full potential offered by AR for educative environments, a set of recommendations are provided in light of the findings made within this analysis and found in other educational research literature.

Firstly, the study thus underscores a pressing need for the development of AR tools for universal access adaptable in all learning environments ranging from well-resourced to under-resourced settings. This means that the priority has to be for the AR solutions to be developed at a low cost but in scalable form, easy to be adopted and used with the diverse infrastructures in education, allowing open doors for innovative ways of learning across socio-economic differences.Secondly, pedagogical integration of AR technologies is to get aligned with learning theories and frameworks of good repute to gain maximum educational advantages. More specifically, AR experiences should be designed and developed based on constructivist principles that promote active, inquiry-based learning, which keeps students engaged in the construction of knowledge while exploring and interacting with AR content.

Moreover, the training and development programs of teachers should be enriched through offering comprehensive training on the effective use of AR in the teaching and learning process. The educators need to possess the relevant competencies and knowledge to effectively embed AR technologies into pedagogical practices, hence creating an environment that is also conducive to modern teaching practices.In addition, for the future research purposes, the agenda should focus on the longitudinal effects of AR on the learning outcome, motivation and engagement of students. Long term studies are important to understand the impact of AR on the sustained educational achievement and the determination of the best practice through which AR can be integrated into the curricula.

Finally, it is recommended that there should be collaboration between educators, researchers, and AR developers to ensure AR tools and applications are pedagogically sound and closely linked with curricular goals. Hence, such an integrated approach might result in a co-created AR educational content that would be both educationally effective and student-appealing.

Therefore, the integration of AR in chemistry education potentially offers revolutionary enrichment of learning experiences and outcomes. The strict adherence of stakeholders to the recommendations could serve as an obligation that AR technologies are exploited in a pedagogically sound, equitable, and educationally improvement-sustaining manner.

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Author Information

Nguyen Mau Duc

https://orcid.org/0000-0002-4414-6613

Hanoi National University of Education

Viet Nam

Contact e-mail: *nmduc@hnue.edu.vn*

Nguyen Vinh Quang

https://orcid.org/0009-0006-2368-8305

Hanoi National University of Education

Viet Nam