Bibliometric analysis of augmented reality in chemistry education over the past decade

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ABSTRACT

Numerous studies have delved into the application of augmented reality (AR) in chemistry education, focusing on specific topics, equipment requirements, and advantages. However, there remains a notable dearth of research examining the evolutionary characteristics of AR in this context. This study, employing bibliometric analysis on 66 articles spanning from 2012 to 2022, reveals that research primarily revolves around pedagogical approaches and AR technology development, particularly in kindergarten to 12th grade (K-12) education. Despite the United States exhibiting the highest publication frequency, there is a significant absence of studies addressing emotions, cognition, and physiological changes. Shedding light on these research gaps, this study underscores the need for further exploration into the cognitive, emotional, and physiological aspects of AR integration in chemistry education. Ultimately, the insights gleaned from this study offer valuable guidance for researchers, educators, and practitioners alike, facilitating the advancement and effective application of augmented reality in chemistry education (ARCE).

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1. INTRODUCTION

Augmented reality (AR) is a technology that relies on cameras to capture the real world, superimposes digital technology on the physical environment, and enhances users' perception of the natural world [1]–[3]. The application of AR in education has long been a topic of interest and is also one of the most promising technologies in higher education and K12 education [4]–[6]. The interactive features of AR can create a more stimulating learning environment and help learners get better learning outcomes [7]. The most popular fields for AR include construction and engineering education [8], [9], health education [10], [11], art education [12]–[14], and science education [15], [16]. These studies point to the potential of using AR in almost all areas of education [17]. AR could enable these concepts to be better visualized. Hence, this study focuses on chemistry education and seeks to provide suggestions for the application of augmented reality in chemistry education (ARCE) by identifying research trends and themes in this area. There is already an article summarizing the applications of AR in topics in chemistry, the equipment used as well as advantages and disadvantages of ARCE [18]. However, there does not seem to be any study investigating the trends in the application of AR [18]. Hence, this study seeks to address this research gap by employing a bibliometric analysis to comprehensively investigate the evolutionary characteristics of ARCE. This would aid in designing chemistry education environments for integration of AR.

Hence, this study proposes the following three research questions: i) RQ1. What are the predominant keywords in ARCE research over the past decade?; ii) RQ2. Who are the leading authors in ARCE research over the past decade and which articles have garnered the highest number of citations over the past decade?; and iii) RQ3. Which countries and academic institutions have contributed the most to ARCE research over the past decade?

2. LITERATURE REVIEW

AR is primarily a technology that displays both the natural world and the physical world at the same time [19], [20]. AR usually has three modes: image-based AR, projection-based AR and superimposition-based AR. Image-based AR uses specific images or markers as triggers to superimpose virtual content on them, enabling users to interact with images in the real world [21], [22]. Projection-based AR is the use of projection technology to project virtual content onto objects or surfaces in the real world to create an immersive AR experience [23], [24].

Superimposition-based AR superimposes virtual content on objects in the real world so that it blends with the environment to achieve a realistic AR effect [25]. There is a significant application of AR technologies in education. Radu [26] listed the positive and negative effects of AR experiences on student learning in education using meta-review and cross-media analysis. Cheng and Tsai [27] explored how AR can help science learning while Sırakaya and Sırakaya [28] used a systematic review method to explore the application of AR in Science, Technology, Engineering, and Math (STEM) education. Murat and Gökçe [29] used a systematic review method to explore the advantages and disadvantages of AR in education. However, most of these reviews are not specific to the field of chemistry education, nor do they comprehensively report the research progress made in recent years.

Bibliometric analysis, which is a quantitative method of analyzing academic literature by identifying topics, keywords, publications, journals, and conclusions can be used to analyze trends and themes in chemistry education [30]. Bibliometric methods and a systematic literature review has been used to study trends and topics in virtual reality in education [31]. Similarly, this study uses bibliometric analysis to analyze AR application trends and themes in instruction for chemistry education.

3. METHOD

3.1. Literature search

This study selected three digital databases: Web of Science, Scopus, and PubMed. These databases have high quality standards. In addition, the serialized data from these databases can be imported into Citespace software. The search combination for this study was "(chemistry or chemical) and ("augmented reality")." The search time frame for this study was between 2012 and 2022. The last search date was January 8, 2023. Four hundred eighty-four journal articles were retrieved, including 55 duplicates, and these results were deleted. The number of remaining research articles is 429.

3.2. Inclusion and exclusion criteria

During the literature screening stage, the titles and abstracts were initially screened based on five criteria (language, subject, time, accessibility, and type) as in Figure 1, which led to the inclusion of 69 records and the exclusion of 360 records. Subsequently, the researchers downloaded papers based on criterion d, accessibility, resulting in the inclusion of 66 records and the exclusion of three records. The selected articles were further assessed for their suitability for the study, and then coded. After independent reviews by two researchers, the consistency of the coding was determined, and disagreements were resolved through discussion, resulting in 100% agreement.

3.3. Analysis

The initial stage of analysis in this study involved importing the 66 article entries into Citespace software to conduct a comprehensive analysis of the data and identify key themes in the literature. Citespace software enables the visualization and analysis of key research directions and academic collaboration patterns in literature [32]. After importing the article entries into Citespace software, various parameters were set to refine the analysis process, including time frame, keyword selection, and citation thresholds [32]. This meticulous approach ensured a thorough examination of the literature landscape, allowing for the identification of emerging trends and influential works [32].

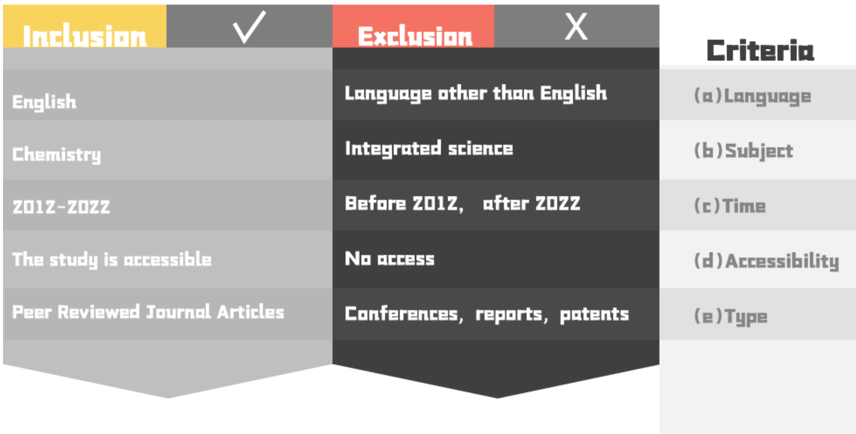

Figure 1. Selection and exclusion criteria diagram

4. BIBLIOMETRIC ANALYSIS RESULTS

4.1. Publication trends of augmented reality in chemistry education articles

Figure 2 presents the publication trends of ARCE articles from 2012 to 2022. By analyzing the data, several notable findings were identified. Firstly, the number of published articles on ARCE has exhibited an upward trend over the past decade, with a steady increase from 2012 to 2020. The most significant surge in publications occurred between 2019 and 2020, with the number of articles nearly quadrupling. Moreover, the number of publications has stabilized at 15 per year in both 2021 and 2022. The sharp increase in ARCE research in 2020 can be attributed to the COVID-19 pandemic [31], which has prompted many educational institutions to switch to online teaching, and AR was a useful tool in facilitating online chemistry education. Furthermore, the accessibility of AR has been enhanced by the development of mobile technology and devices [33].

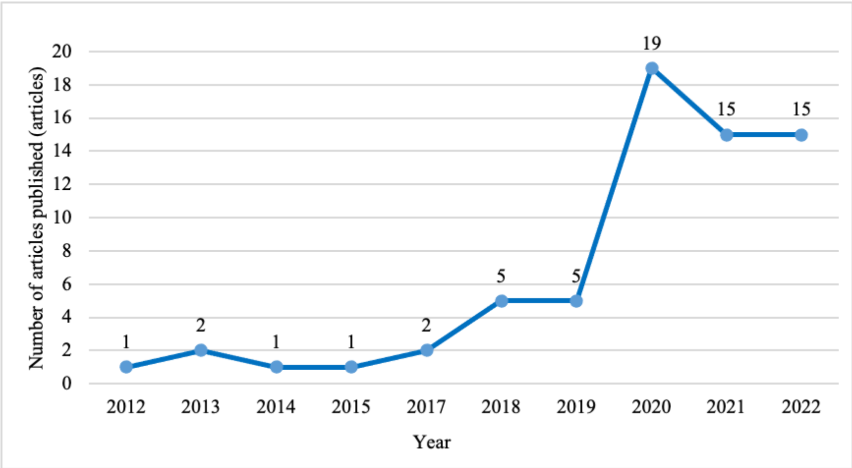

Figure 2. Trend diagram of publication of articles on ARCE from 2012 to 2022

4.2. Keyword analysis

In this section, a bibliometric analysis of keywords was conducted to gather understanding on the relationships between keywords, making it easier to identify trends, patterns, and connections [34]. At the same time, it highlights the content related to AR and chemistry education. The keyword diagram is is shown in Figure 3. The keyword co-occurrence diagram is shown in Figure 3(a), the keyword timeline diagram in Figure 3(b).

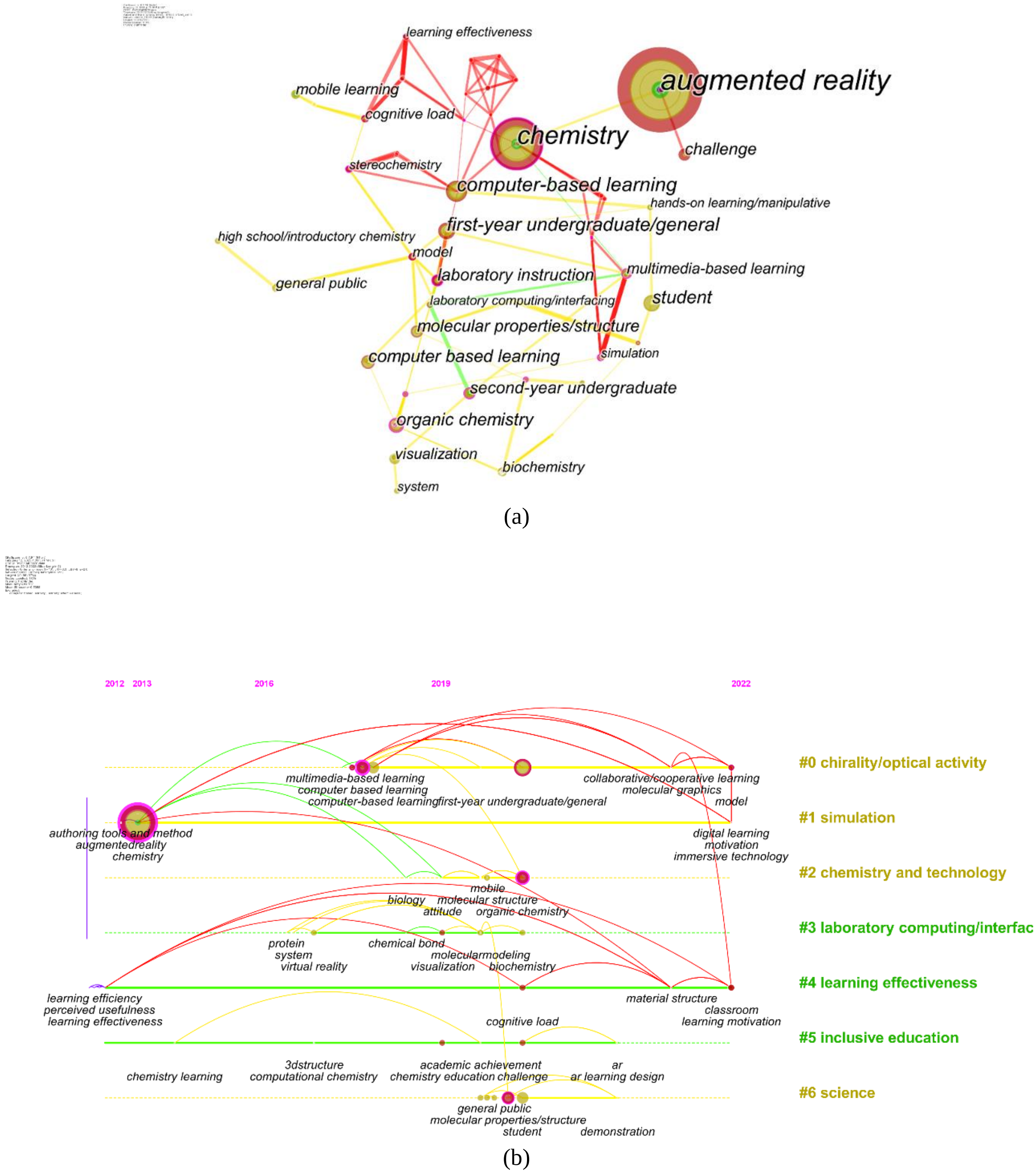

Figure 3. Keywords with the (a) co-occurrence diagram and (b) timeline diagram

As shown in the Figure 3(a), this study found that the keywords are mainly divided into three clusters. The keywords in the red cluster are chemistry, computer-based learning, laboratory instruction, multimedia-based learning, first-year undergraduate/general, second-year undergraduate, challenge, model, and organic chemistry. These keywords discuss various commonly used technological approaches such as AR, computer-based learning [35]–[37], multimedia-based learning [38]. These techniques provide laboratory instruction and models to first- and second-year undergraduate students encountering challenging topics in organic chemistry.

The main keywords in the green clusters are AR, chemistry, laboratory computing/interfacing, second-year undergraduate, and multimedia-based learning. These terms are interlinked and have been integrated into the second-year undergraduate curriculum to improve the students' learning outcomes. Moreover, the multimedia-based learning approaches are adopted as a supplementary instructional strategy to augment the effectiveness of AR and laboratory computing/interfacing techniques.

Yellow clusters show the primary keywords are computer-based learning, molecular properties/structure, student, biochemistry, and high school/introductory chemistry. These keywords discuss the implementation of computer-based learning in the field of biochemistry, with a focus on the study of molecular properties and structure. These computer-based tools have been developed to assist high school and introductory chemistry students in comprehending complex biochemistry concepts. By utilizing these tools, students can interact with and manipulate molecular structures more engagingly and interactively, which leads to a more profound understanding of the concepts.

As shown in the Figure 3(b), the clustering and critical nodes of the keyword timeline diagram intuitively reveal the key literature and evolution context of research in this field, indicating the development trend of research topics from far to near. By dividing the 9 clusters, we can start from 3 perspectives, the first is the perspective of AR application development (cluster #0, #1, #3, #8), the second is the perspective of chemical education (cluster #2, #6), and the third is the perspective of teaching effect (cluster #4, #5); i) Cluster #0, #1, #3, #8-AR teaching method perspective. The clustering involves various teaching methods, including computer-based, multimedia-based, cooperative, digital, immersive, and mobile learning. These approaches utilize authoring tools and methods to create AR learning systems incorporating visual and audio elements to facilitate student motivation and understanding. Such technology allows for enhanced visualization of AR systems, leading to improved comprehension of molecular structures and chemical properties [39]; ii) Cluster #2, #6--AR application and development perspective. The clustering pertains to developing and implementing AR (authoring tools and methods) in chemistry education, specifically focusing on studying molecular properties and structure. These tools and methods are designed to facilitate the understanding of complex chemistry concepts for students and the public. The use of AR (authoring tools and methods) enables the creation of interactive and engaging materials that can enhance learning and improve comprehension of molecular structures and chemical properties [35], [37], [40], [41]. The clustering analysis emphasizes the significance of leveraging AR, including authoring tools and methods, as an effective strategy to enhance chemistry education and facilitate knowledge dissemination to a broader range of audiences; iii) Cluster #4, #5 - Evaluation of AR applications. The clustering pertains to using ARCE and its impact on learning motivation, efficiency, perceived usefulness, learning effectiveness, and cognitive load. AR is a technology that superimposes digital information onto the real-world environment, creating an immersive and interactive experience for students [38]. The incorporation of AR in the classroom can enhance learning motivation, effectiveness, and efficiency by providing a more engaging and interactive learning experience [42]. The perceived usefulness of AR is a crucial factor that can affect its effectiveness in education, as students must recognize the practical value of this technology to fully engage with it [42]. However, the use of AR can also increase cognitive load, negatively impacting learning [43]. The clustering underscores the significance of comprehending both the potential advantages and limitations of ARCE, in order to optimize its efficacy and facilitate successful learning outcomes.

It can be seen from Figure 3 that the application of ARCE is divided into two stages: i) AR assists chemistry teaching in higher education (2012-2019). In this stage, the principal values of learning efficiency and perceived usefulness are the largest. This phase deals with using mobile AR in teaching chemistry in higher education and its impact on learning efficiency and perceived usefulness. For example, Habig [44] used AR software to explore the learning effects of college students and their attitudes toward applications. ii) AR assists in chemistry teaching at the K12 stage (2020-2022). This phase is related to using ARCE for K12 students, focusing on chemical structures and their impact on learning motivation and cognitive load. For example, Liu *et al.* [45] used AR to integrate multiple external representations (text, pictures, 3D models, operations) to explore junior high school students' technology perception and learning motivation.

The word frequency detection technology in citespace is utilized to identify keywords with significant frequency changes, allowing for the identification of frontier fields and development trends in the subject area [46]. As shown in Figure 4, the subject's frontier fields and development trends are judged based on the magnitude of the change in word frequency rather than just the frequency. As demonstrated in Figure 4, the subject's development trends are judged based on the magnitude of the change in word frequency rather than just the frequency. Analysis of Figures 3 and 4 indicates that from 2012 to 2019, computer-based AR and Mobile AR were utilized as tools for enhancing higher chemistry education, while evaluating the usefulness and learning effects of mobile AR. From 2020 to 2022, the integration of mobile AR-based digital learning into the chemistry education process continued, along with the incorporation of cooperative and immersive learning using various teaching methods. Researchers began to evaluate the impact of AR systems on learning motivation and cognitive load regarding chemical molecular structure among high school and lower-grade students.

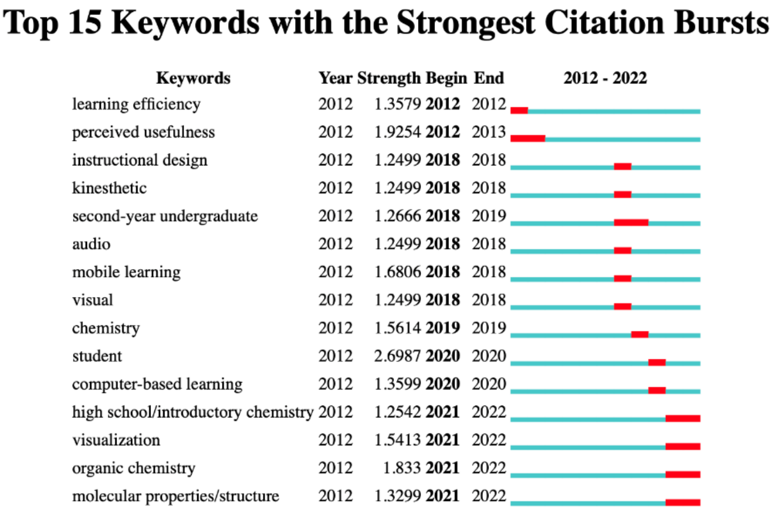

Figure 4. Keywords with the strongest citation bursts diagram

4.3. Literature analysis

Figure 5 lists the cited literature on ARCE. The higher the frequency of literature being cited by other literature, the greater its importance in this field. Murat and Gökçe [29], Eriksen *et al.* [47], Sanii [48] and Cai *et al.* [49] are significant because of their high citation frequency. They have an important influence in the field of ARCE. Murat and Gökçe [29] analyzes the advantages and challenges of AR in education. Eriksen *et al.* [47] described how to use free software to make a simple AR app to visualize any 3D chemistry model of a university course. Cai *et al.* [49] developed an AR tool to study junior high school students' attitudes and learning effects. Sanii [48] explores molecules in 3D using mobile device-based AR to help students visualize.

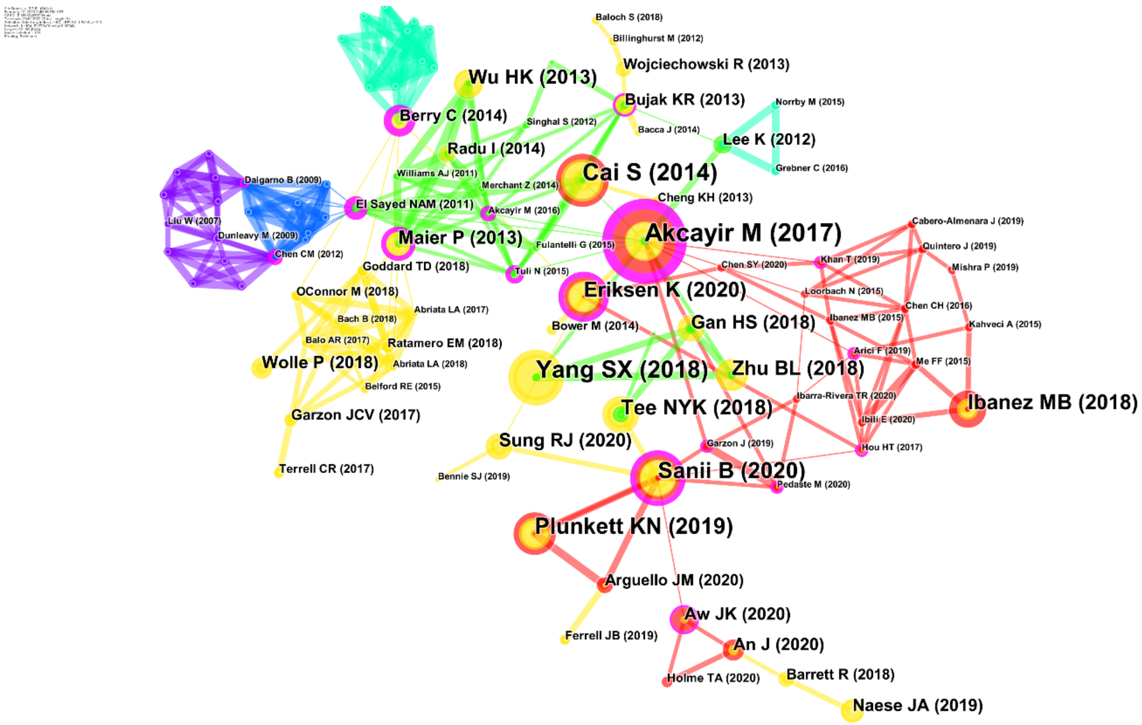

Figure 5. Keywords with the co-citation analysis diagram

4.4. Country and institution mix analysis

As in Figure 6, the United States has the highest publication frequency, followed by China, Singapore, Chile, and Germany. The United States is at the forefront of ARCE research and has made significant contributions to this field. In terms of centrality, the United States has a score of 0.47, indicating that it holds a core position in the research cooperation network and collaborates with most countries and institutions. Prominent research institutions in this area include the University of East Anglia, the University of Toronto Scarborough, and the Australian Catholic University.

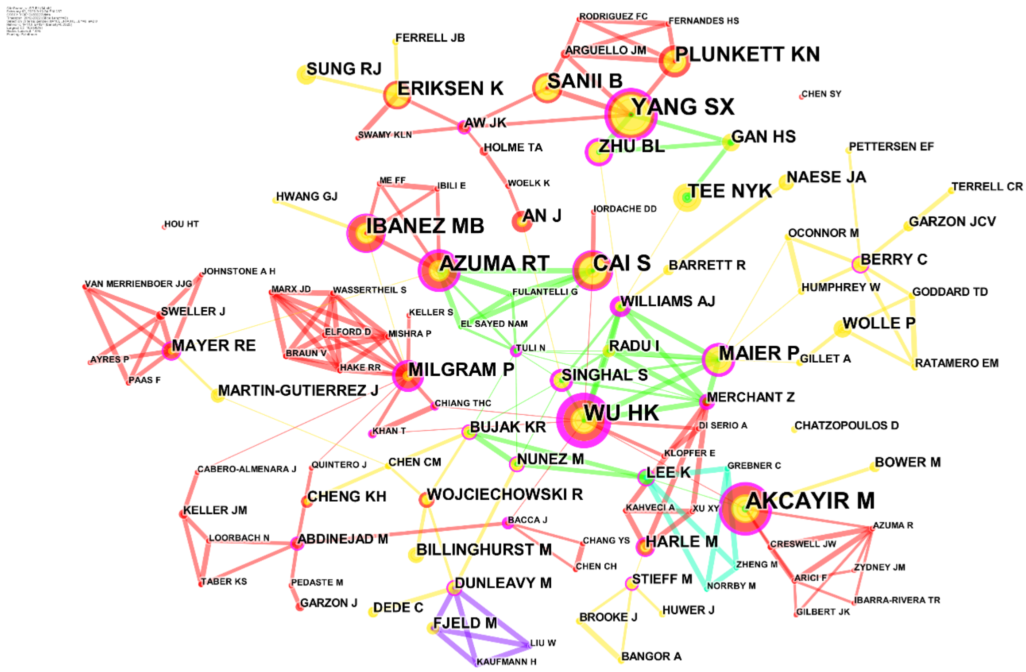

Figure 6. Hybrid network diagram of country and institution

5. DISCUSSION

The keywords in ARCE research reflect the trends and focus of the research. By synthesizing the keywords from existing literature, one can gain insights into the development trends and research dynamics in the field [50]. This study identified three major research themes that are concurrently evolving: i) exploring instructional methods for AR-assisted teaching [39]; ii) building AR systems and applications for chemistry education [35], [37], [41]; and iii) examining the role of ARCE through instructional design [42]. However, compared to the visual and auditory modalities, research on ARCE is still in its early stages. Future studies are encouraged to implement empirical interventions to further elucidate the specific implementation effects of ARCE. Researchers often discuss the variations in technological interventions across different educational stages and levels [51].

Therefore, it is necessary to examine AR research participants at different stages of chemistry learning. This study identified two major research stages in ARCE: i) AR-assisted higher education chemistry teaching (2012-2019): In this stage, participants primarily focused on the perceived usefulness and ease of use of the technology and ii) AR-enhanced kindergarten to 12th grade (K-12) chemistry teaching (2020-2022): participants in this stage experienced rapid development in emotional, cognitive, and physical aspects [52]. Existing research in this stage primarily focuses on the influence of technology on students' learning motivation and cognitive load. Consequently, more research is needed to investigate emotional and behavioral changes in K-12 chemistry learning facilitated by AR. Wearable AR devices hold promise for conveniently detecting teenagers' emotional and behavioral changes (under appropriate ethical conditions), thereby potentially intervening in students' potential negative emotions and behaviors. While the findings of this study have extended the existing literature on the use of AR technology in chemistry education, there exist certain limitations. To ensure a more comprehensive understanding of this topic, future research efforts should prioritize the inclusion of articles published in languages other than English to attain a more diverse and inclusive perspective. Additionally, the search process could be expanded to include a wider range of databases, article types, and keywords to obtain a more comprehensive understanding of the relevant literature. Strengths and challenges are also important, but this is not the main content of this study. Therefore, this study does not describe too much.

6. CONCLUSION

In conclusion, this study utilized bibliometric analysis to explore the evolutionary characteristics, AR properties, instructional strategies, and techniques of AR technology in the context of chemistry education. It sheds light on significant implications for advancing the understanding and practice of ARCE. The findings of this study provide important recommendations for researchers, educators, and practitioners. First, researchers should pay more attention to the development of teaching methods and AR technology, while strengthening empirical intervention studies to explore this area in depth. Second, educators need to recognize that current research is primarily focused on AR-assisted chemistry education at the K-12 level and should work to fill research gaps regarding affective, cognitive, and physiological changes. In summary, this study provides researchers with directions for further in-depth research, provides educators with suggestions for improving teaching practices, and provides practitioners with reasonable technology application strategies to promote the application of AR technology in chemistry. Developments and applications in education.

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