Review Article

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Using innovative technology tools in organic chemistry education: bibliometric analysis

https://doi.org/10.1515/cti-2024-0055
Received June 14, 2024; accepted November 2, 2024; published online December 3, 2024

Abstract: This study focused on investigating the usage of popular innovative technology tools (augmented reality-AR, virtual reality-VR, artificial intelligence-AI, and 3D printing) in organic chemistry education. Although there is bibliometric analysis for the exploration of using innovative technology in educational context, there is further need for research focused on their usage in organic chemistry. Vosviewer and Biblioshiny software were used for bibliometric procedures. The Scopus database was selected to trace the articles published in journals. Following the eligibility process, the study was conducted with 30 articles for the time frame between January 2014 and June 2024. Performance analysis was utilized to reveal publications and citation trends with the top contributors. Bibliographic mapping was used to comprehend the conceptual, intellectual, and social structures of the retrieved data. The results revealed that articles on innovative technology tools have enormously increased in organic chemistry education recently. We found that the first innovative tool among the selected ones that is utilized in organic chemistry education is 3D printing while AI is the latest tool to start to be used in this scope. Although artificial intelligence seems to be the least studied tool among them, its popularity has recently seen an acceleration. VR and AR had the highest average citations per publication.

Keywords: organic chemistry education; augmented reality; virtual reality; artificial intelligence; 3D printing

1 Introduction

This study aimed to explore organic chemistry education studies which focused on augmented reality (AR), virtual reality (VR), artificial intelligence (AI), and 3D printing under the name of innovative technology tools (IT). Innovative technology provides a profoundly different perspective for organic chemistry laboratories. In particular, these tools can be used to teach abstract subjects when there is no opportunity to make direct observations or gain laboratory experience (Broyer et al., 2021). For instance, VR can offer students a valuable chance to experience what the world looks like at the molecular level (Pence, 2020); however, on the negative side, these applications hinder collaboration with peers and instructors as well as requiring the use of equipment (Babak, 2020). For instance, to successfully integrate VR tools, headsets and computer screens are used, which block out the real world (Babak, 2020). On the positive side, many organic chemistry researchers have stated that VR technology enhances learning among students (Pietikäinen et al., 2021), aids in improving spatial ability (Serrano-Ausejo & Mårell-Olsson, 2024) and increases 21st century skills (Serrano-Ausejo & Mårell-Olsson, 2024). For instance, Serrano-Ausejo and Mårell-Olsson (2024) used VR and AR in visualizing molecules in 3D to improve students' understanding of molecules representation in stereochemistry and to support their spatial ability and to develop 21st-century skills (i.e., complex problem solving). Echeverri-Jimenez and Oliver-Hoyo (2024) worked on creating a VR Learning Environments to facilitate students' abilities to recognize 3D characteristics from 2D

No ethics committee approval was obtained because the research is a bibliometric analysis.

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representations. Dunnagan et al. (2020) developed a VR laboratory in WondaVR so that students can use an infrared spectrometer and explain an unknown structure from the resulting infrared spectrum. The independent variables were method of instruction; a VR learning experience and a traditional instrumentation-based face-to-face laboratory. All the students belonging to control and treatment groups were provided with a lab worksheet to complete as part of their grade for the lab. Those in the treatment group also received a follow-up survey as soon as their lab was finished. The dependent variables were learning outcomes related to the use of the infrared spectroscopy virtual reality learning experience in an organic chemistry laboratory, in comparison to the control group that was taught by teaching assistants in a traditional lab setting. The researchers compared the outcomes for short- and long-term recall of students, attended traditional or VR laboratory experiments. Both groups did the same experiment in a lab. Results indicate that there are no significant differences in learning outcomes between the two groups, which points to the possibility of using this tool without the need for an organic chemistry lab in the condition that distance education must be used. Students who tried the VR experience reported that they were highly satisfied with the product and did not experience any hindrance in terms of usability. Similarly, Kounlaxay et al. (2022) also designed interactive organic chemistry experiments, in which chemical reactions were simulated through mixing chemicals. Moreover, Pietikäinen and colleagues (2021) provided the design and implementation of new virtual reality software named VRChem for visualizing and manipulating organic molecules using a virtual reality system. As it is seen, the researchers preferred to use VR technology for various topics. For instance, Ferrell et al. (2019) designed educational VR activity based on interactive molecular dynamics in virtual reality (iMD-VR) to demonstrate chemical concepts and enable students to participate in exploring molecular structures, motions, and interactions. Organic chemistry students were asked to fulfill a sample task to pull a methane molecule through a carbon nanotube with iMD-VR. Results indicated that this activity was useful to improve students' understanding and motivation. In a similar fashion, Edwards et al., (2019) developed the VR Multi-sensory Classroom (VRMC) to support high engagement, motivation, interest and organic chemistry learning.

Similar to VR, many researchers have largely benefitted from AR technology to improve students' visualization of three-dimensional chemical structures (e.g., Abdinejad et al., 2021; Babak, 2020; Eriksen et al., 2020; Habig, 2020). With the help of AR, digital elements like texts, directional signs, 3D models, or animations can directly be projected on real-world objects (Habig, 2020). For instance, Abdinejad and her colleagues (2021) used an ARchemy app, developed to help students visualize difficult 3D concepts, and at the end of the study they got positive feedback in regard to the value and perceived usefulness of this app for organic chemistry students. Additionally, Aw and colleagues (2020) developed and described their AR project, which is a free-to-use mobile app called Nucleophile's Point of View (NuPOV). Unlike other AR apps, NuPOV allows organic chemistry students to interact, using their fingers, with 3D molecules and understand at a deeper level through an individualized and self-directed learning experience. They also reported that the students appreciate the AR app. AR is a technology that incorporates virtual elements with the real world (Azuma, 1997).

The preference of 3D printing in organic chemistry education has become more prevalent in the recent decade. Crowe and colleagues (2021) used 3D printing in a middle school for teaching about water/surface interactions on both hydrophilic and hydrophobic surfaces. They reported that the 3D-printed method, compared to simply holding the smart device by hand, provided better-quality images and an improved data acquisition experience when measuring the contact angle. Moreover, Renner and Griesbeck (2020) presents a 3D printing lab in which students can learn the basics of 3D printing using a predesigned 3D-printed continuous flow reactor for photochemical reactions, especially for photo oxygenations.

As another innovative technology, Artificial Intelligence (AI) has a great impact in our lives today as it performs tasks without the need for human interference. Its impact is already visible in numerous industries which undoubtedly include chemistry education and is believed to shape the future of chemistry education (Pence, 2020). For instance, many researchers have been interested in using AI to develop new drugs (Maryasin et al.,2018; Peiretti & Bruner, 2018). Moreover, AI applications can be beneficial for chemistry education by offering more personalized learning opportunities for students, by helping teachers assess students or by facilitating the teaching of organic chemistry concepts.

There are few studies that have run bibliometric analysis for innovative technology tools (Botero-Gómez et al., 2023) and organic chemistry (Hassan et al., 2022) in educational context, which are carried out as separate studies. The scientific method defined as bibliometric analysis deals with a large-scale literature database to evaluate the contributions to a field of research, by countries, institutions, authors, and journals. Currently, its popularity has steadily risen in many fields (Pala, 2023; Pocan, 2023). For instance, Botero-Gómez et al. (2023) conducted a bibliometric analysis to investigate the trends and evolution of the application of virtual tools in teaching-learning processes. Their search query resulted in 104 articles. The results of this study allowed the identification of the most influential contributions, authors, and journals, as well as the trends of research carried out in the field. In the related literature, there are a few bibliometric analyses focused on organic chemistry education. Hassan et al. (2022), for instance, presented a bibliometric analysis to illustrate the organic chemistry education's trends in the 2011–2020-time frame. For this analysis, they investigated 1056 papers from the Scopus database. Their study identified an increasing growth rate of literature on organic chemistry education. The United States was also reported as the top contributor to organic chemistry education research, followed by Canada. To provide another instance, Evdokimenkova and Soboleva (2020) conducted the bibliometric analysis and searched the term "organic chemistry" in the Web of Science with the limitation by the country (Russia) and time periods by decades between 1990 and 2019. They investigated 26,958 publications. Their study revealed that the number of publications in organic chemistry has increased overall. Particularly, the interest of organic chemists towards the area of medical and physical chemistry is increasing, whereas the fraction of research related to biochemistry and molecular biology is decreasing. Moreover, they reported that Russian scientists prefer to publish papers in domestic journals, which possess low citations. To the best of our knowledge, there are no bibliometric studies that solely examine the use of IT, which are selected for this study, in the context of organic chemistry education. In the present study, unlike the other bibliometric studies in this field, two prime bibliometric procedures (Performance analysis and Science/Bibliometric mapping) were used to discover the research trends of using IT in organic chemistry education. Thus, by analyzing the use of all keywords included in selected IT along with organic chemistry in the educational context, our aim is to make a significant contribution to the literature.

2 Methodology

2.1 Database selection and search query

The database of the study was determined as Scopus because many researchers have used Scopus to trace the articles published in journals (i.e. Gao et al. 2022; García-Tudela & Marín-Marín, 2023) because this is an index and selective full text database of educational research. For instance, Hassan et al. (2022) used Scopus database to illustrate the organic chemistry education's trends for their bibliometric analysis study. Indeed, Scopus provides at least two times more research metrics than other available abstract and citation databases (Scopus, 2024). Besides, it is one of the databases that was used by the primary bibliometric analysis tools, such as Vosviewer and Biblioshiny. In this study, the data were analyzed through PRISMA (2020) guidelines. There are three phases according to PRISMA (Moher et al., 2009); identification, screening, and inclusion. In the following, each phase is introduced.

Identification: This phase included a data mining process and the control of duplicate publications. No duplicate results were identified in this study. The data was obtained with the following retrieval strategy: (TITLE-ABS-KEY) ("organic chemistry" AND "education") AND (TITLE-ABS-KEY) ("augmented reality" OR "artificial intelligence" OR "3D print*" OR "virtual reality"). The query yielded a total of 56 publications (see Figure 1).

Screening: This phase consists of selection according to the inclusion/exclusion criteria and the eligibility process. The inclusion and exclusion criteria of the studies were as below:

- The screening was limited to the Title, Abstract, and Keywords of the publications.
- Languages other than English are excluded to be able to read all parts of the article by the authors for the eligibility process.
- In document type, other than the journal articles are excluded (i.e., proceeding papers, book chapters, editorial materials, meeting abstracts).

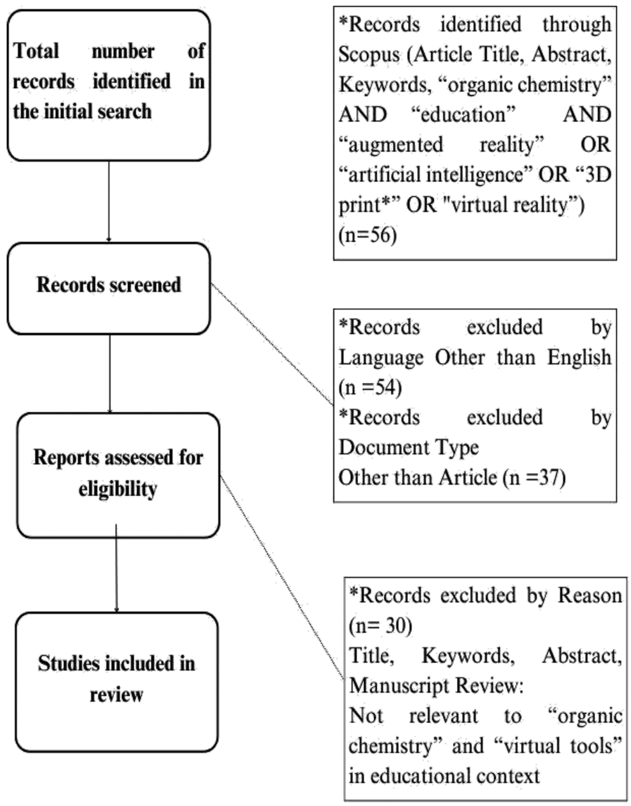

Figure 1: Prisma flow diagram for the data selection [adapted from PRISMA (2020)].

– The publication must focus on using innovative technology tools (i.e., augmented reality) in organic chemistry education.

Removing the languages other than English left 56 publications (see Figure 1). Moreover, having selected the article as the only type in terms of the document type, 38 publications appeared. The reason behind this selection is these 'journal papers' are deemed reliable because of peer review. Moreover, publications focusing on research trends in science education have tended to focus on particular journals as the content of their investigations (i.e., Lin et al., 2019). Then, these 38 articles were scrutinized regarding the abstract as well as the titles by two researchers to ensure that they fit the criteria for the study. At this stage, studies were dismissed if the articles were not focused on innovative technology tools in organic chemistry education. For instance, one article, titled "Information and Communication Technologies Combined with Mixed Reality as Supporting Tools in Medical Education" was deleted from the dataset because this article was about the implication of IT in medical education instead of organic chemistry. Moreover, another article named "A Case Study on Using Uncritical Inference Test to Promote Malaysian College Students' Deeper Thinking in Organic Chemistry" was removed from the list because it does not focus on the implications of IT in organic chemistry learning.

Inclusion: After reading and screening 38 articles, 30 of them were deemed eligible in the final data analysis as the last phase of the PRISMA (2020) protocol, Inclusion. These 30 articles were listed in Appendix 1 in terms of the year of publication, total citations (TC) and type of innovative technology tools used in the organic chemistry education. Appendix 1 could also be useful to see which study is the most cited one in descending order for each innovative technology tool used in this study.

As seen in Figure 2, a considerable proportion of the articles in the dataset were related to using Virtual Reality (30 %), 3D printing (30 %) and Augmented Reality (20 %) in organic chemistry education. Therefore, it would be expected that the articles with the highest citation would follow the same order above, as also presented in Appendix 1.

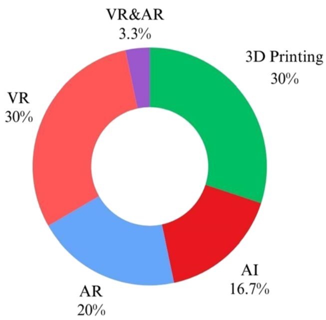

Figure 2: The percentages of the innovative technology tools used in 30 articles. Augmented Reality (AR) is represented by blue color, Virtual Reality (VR) by orange color, Artificial Intelligence (AI) by red color, 3D Printing by green color and the study including both VR&AR by purple.

2.2 Data analysis

Performance analysis and Science/Bibliometric mapping were used to discover the research trends of using innovative technology in organic chemistry education. Performance analysis is an established quantitative method for assessing academic output for productivity, quality, and scientific impact by detecting principal contributors. Science or bibliometric mapping analysis presents the structural and dynamic aspects of the data extracted from the research (Börner et al., 2003). In the current study, we used Vosviewer and Biblioshiny in data visualization and in discovering the relations in citations, co-authorship, and bibliographic coupling.

3 Findings and discussion

3.1 Overview of the analyzed data set

Table 1 shows the information on 30 articles published in the period between January 2014 and June 2024, which was extracted from the Scopus database. All articles related to innovative technology tools were published by 13 different journals and 123 authors, who used 115 different authors keywords. Scopus records include two types of keywords: Author Keywords, and Keywords Plus. Author Keywords comprise a list of terms that authors have chosen themselves to represent the content of their paper (Li et al., 2009). On the other hand, Keywords Plus are generated automatically by computer algorithm, which consist of words or phrases that can appear anywhere and are not limited to the author's keywords or content, even including the titles of an article's references. For this study, we used Authors Keywords because although Keywords Plus is effective for searching articles, it is less comprehensive in representing an article's content. The average number of co-authors in each publication is 4.33. This value is compatible with the other disciplines (i.e., green marketing, social sciences research) where the most common authorship numbers consist of more than 3 authors (Saleem et al., 2021). Moreover, considering the results obtained from average citations per publication (21.97), we can say that "using innovative technology tools in organic chemistry education" is a topic that has not only gained a place but also solidified its position in the academic sphere. Besides, the percentage of international co-authorships (23.33) demonstrates that a significant portion of the studies conducted in this field have included international collaboration. Similarly, Prahani et al. (2024) also observed high collaboration percentage (21.82) in their bibliometric study, aimed to analyze the scientific creativity literature in the last 20 years. This means that the scientific creativity field is also likely has a high collaboration index. However, some other bibliometric studies in the literature did not find high percentage of international co-authorships. For instance, Mata et al. (2024) indicated moderate level of global collaboration (17.11) in their bibliometrics study focused on new software product development and the researchers stated the necessity of improvement of international cooperation in this field.

Table 1 also includes descriptive statistics for VR, 3D, AR, and AI individually in addition to innovative tool (IT) statistics. As presented in Table 1, 3D printing was the first innovative tool among the selected ones to be used in

Table 1: Descriptive statistics of the articles in the dataset focused on AR, VR, AI, and 3D printing as IT for January 2014–June 2024 timespan.

Description	VR	3D	AR	AI	IT
Timespan	2017–24	2014–23	2019–24	2022–24	2014–24
Journals	6	3	3	3	13
Articles	9	9	6	5	30
Document average age	3.67	4.78	3	1	3.3
Average citations per documents	33.44	17.22	31.17	3	21.97
Author's keywords	40	34	38	29	115
Authors	35	28	30	29	123
Co-authors per documents	4.11	3.11	5.5	6	4.33
International co-authorship %	11.11	11.11	33.33	60	23.33

organic chemistry education while AI is the most recent one to start to be used in this context. VR and AR had the highest average citations per publication.

What is more, looking at the statistics for co-authors per publication and international authorship, the highest values belong to AI. In the other studies made, there have not been observed a relation between being the most recent or a higher value for co-authors per publication and international authorship (i.e., Authors 1, 2). In addition to this, to verify this relationship or lack of relationship, we have also compared the co-authors per publication and international authorship values for 3D printing (which has the oldest average age in this dataset) with AI (which is the most recent one) between the years 2022–2024 in Table 2. As can be seen, the studies with 3D still have lower co-authors per publication and international co-authorship values compared to those of AI. Indeed, the recent studies that are made on 3D do not represent any international collaborations.

In this dataset, we have found three studies about 3D printing for the period 2022 January to 2024 June, all of which belonged to the year 2023. The first of these is titled “Hydrophilic and Conductive 3D-Printed Electrocatalysts in Hydrogen Evolution Reaction for Undergraduate Experiments”. The current affiliation country of all 5 authors of this article is seen to be China. The second article is named “Do-It-Yourself 5-Color 3D Printing of Molecular Orbitals and Electron Density Surfaces”, and its authors are from the USA. The last one is titled “The Approach to Aromatherapy and Essential Oils Extraction as a Generating Theme for Teaching Organic Chemistry”, the three authors of which are from Brazil. This demonstrates the point that there has not been international cooperation for the period. However, analyzing the same situation for AI, international collaboration is more common. For example, the first article that was published in 2022, named “A CASE (Computer-Assisted Structure Elucidation) for Bench-Top NMR Systems in the Undergraduate Laboratory for *de Novo* Structure Determination: How Well Can We Do?” boasts the collaboration of 12 authors who are from three different countries (Canada, Spain and Germany). Similarly, another example belonging to AI is an article made by China, the USA, and Saudi Arabia, with the name “Data Integration Method of Multi-source Feedback Evaluation for Remote Teaching Quality”. In addition to these studies, it is observed that many other AI studies in the literature are conducted with significant global collaboration. For instance, Polat et al. (2024) conducted a bibliometric analysis to investigate the educational studies on ChatGPT and observed that each publication had approximately four co-authors (n = 3.96). Moreover, the researchers reported international co-authorship in more than one-

Table 2: Descriptive statistics of the selected articles on artificial intelligence (AI) and 3D printing for January 2022–June 2024 timespan.

Description	3D	AI
Timespan	2022–24	
Articles	3	5
Co-authors per documents	4	6
International co-authorship %	0	60

fourth of the publications (26.42). Radu et al. (2024) also reported 23.54 % of the documents focused on AI and competency-based education have international co-authorship. Furthermore, Fidan and Kasimi (2023) also reported the high percentage of international co-authorships (37.29) in their bibliometric study aimed to examine AI articles in the subject of language education.

3.2 Research productivity in terms of publications and citations

Scopus was used to investigate the distribution of the number and citations of the articles per year. The annual research productivity is demonstrated in Figure 3. According to this graph, the first article appeared in 2014 and was related to using 3D printers in teaching of structure–energy relationships in molecular conformations and in chemical reactions. This article was cited 22 times. Despite the dearth of publications until 2019 as seen in Figure 3, there seems to be a considerable increment in the coming few years. The year 2020 and 2023 had the highest numbers of publications (*n* = 6), while the highest number of citations (*n* = 203) were received in the year 2019. As the year 2024 is not finished yet, the drop in this year can be accepted as normal. The number of articles produced after 2020 (during Covid) constituted 76.66 % of total publications. It seems that most of the articles have been published after the Covid started and later. This finding is also supported by the average age of the articles, which is found to be 3.3.

3.3 Leading countries

The total number of countries that have contributed to the studies conducted on the subject was twenty-two. Out of these countries, Figure 4 depicts the research productivity of the most productive countries in terms of publications and citations. Findings identify that the most productive countries were the USA (*n* = 16), Canada (*n* = 3) and China (*n* = 3). The rest of the countries had two or fewer publications. Figure 4 also shows that the USA (*n* = 374), Malaysia (85), and Canada (*n* = 73) have the highest citations in the related field. As seen in Figure 4, although China had 3 articles, the number of citations was very low. On the contrary, Malaysia had only one article, their number of citations was one of the highest. The unequal distribution of publications and citations among the countries has been seen in the literature very often (i.e., Authors 1, Kaya-Capocci, 2023). We investigate the descriptive statistics of these two countries as presented in Table 3 to better understand the unequal distribution among the countries (see Figure 4). However, because the number of the articles was very low, it is not easy to say what caused this unequal distribution in this situation. When we looked at the article belonging to Malaysia, we found that the article titled “Haptic Virtual Reality and Immersive Learning for Enhanced Organic Chemistry Instruction” is the most cited publication in this dataset.

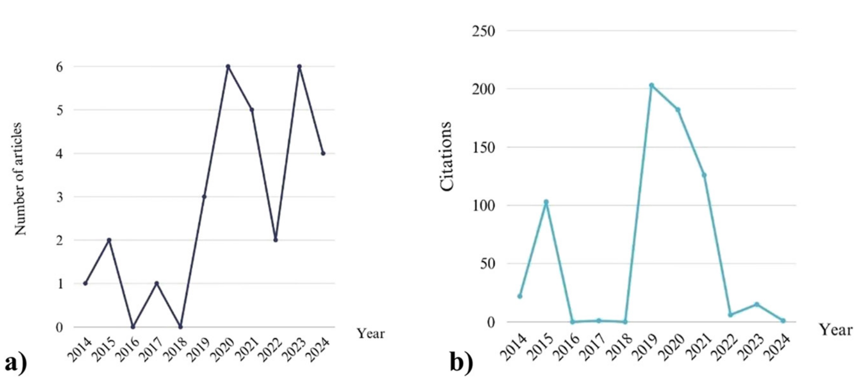

Figure 3: Number of (a) publications and (b) citations per year from January 2014 to June 2024.

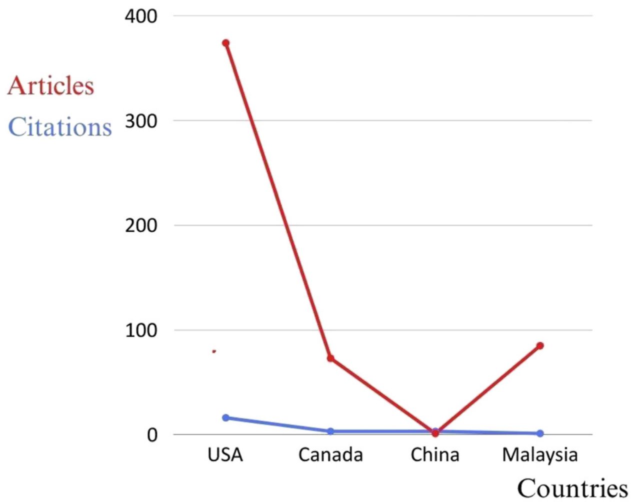

Figure 4: Trends of publications and citations of the countries from January 2014 to June 2024.

Table 3: Descriptive statistics for China and Malaysia.

Countries	China	Malaysia
Documents	3	1
Sources	3	1
Timespan	2017–23	2019
Document average age	3	5
Average citations per documents	0.6667	85
Authors	9	4
Single-authored documents	1	0
Co-authors per documents	3	4
International co-authorship	33.33 %	100 %

3.4 Most productive authors

Table 4 shows the most productive authors with their current institutional affiliation, the total number of publications by each author (TP) and the respective years these publications belong to, the total citations associated with these publications (TC), and the h-index (h). As is seen in Table 4, only seven authors out of 123 authors published more than one paper on the topic. Table 4 also presents the most productive and most cited authors in the dataset. In this table, A.D. Cheok has a very high impact with an h-index of 41, meaning this author has 41 papers with at least 41 citations each. Moreover, top authors' production over time is also presented in Table 4. It is seen that M. T. Gallardo-Williams and C. L. Dunnagan, the most productive and most cited authors, made their two joint publications in the same year (2020). Moreover, A. J. Dood started publications in this field in 2023 and published in 2024.

3.5 Most influential journals

All articles in the database were published by 13 different journals (see Table 1). Journal of Chemical Education produced 60 % of the articles ($n = 18$) in the database and the other journals each published only one article on this topic. Moreover, Journal of Chemical Education had the first published article in the database, named "3D printers can provide an added dimension for teaching structure-energy relationships and STEM publications".

Table 4: The most productive and most cited authors.

Author	TP[b]	Year of publication	h index	TC[a]
M. T. Gallardo-Williams	2	2020	15	113
C. L. Dunnagan	2	2020	4	113
M. Abdinejad	2	2021	18	70
S. Dalili	2	2021	13	70
H. S. Qorbani	2	2021	3	70
A. J. Dood	2	2023 & 2024	9	7
M. Oliver-Hoyo	2	2024	13	2
K. S. Bielawski	1	2019	3	85
R. Prada	1	2019	21	85
A. D. Cheok	1	2019	41	85
B. I. Edwards	1	2019	4	85

[a]TC: The total citations associated with these publications, [b]TP: The total number of publications by each author.

3.6 Most frequently used words in the dataset

115 author's keywords were detected in 30 articles in the dataset (see Table 1). Figure 5 presents a visualization of the top 15 words that appeared most frequently in the database. While the location of the words within the illustration does not have specific meaning, the prominent words with a larger font size are placed in the middle so that they are more visible. The most repeatedly used keywords were "Organic Chemistry" ($n = 20$), "second-year undergraduate" ($n = 11$), "hands-on learning" ($n = 8$), "computer-based learning" ($n = 6$), "molecular modeling" ($n = 6$), "multimedia-based learning" ($n = 6$), "upper-division undergraduate" ($n = 5$), and "virtual reality ($n = 5$)".

To visualize the top 5 keywords' frequency over time, Figure 6 was developed using the Biblioshiny with precise graphical parameters: field as "authors' keyword", occurrences "per year" with no confidence interval with the top 5 keywords considering their maximum frequencies. As seen in Figure 6, during the first five years of our dataset (2014–2018), "organic chemistry" does not show up as an author's keyword in any article. However, during the next 5-year period 2019–2023, this number rose from zero to 14. This number is 4 for the first 6 months of 2024. This is a meaningful trend in the number of authors keywords, signifying the place and importance of "organic chemistry" in such studies.

3.7 Co-authorship network map

Biblioshiny software was employed to conduct a visual analysis of the authors' collaboration network. For this analysis, Figure 7 illustrates authors who co-wrote at least one article. As seen from the thickest linkage in Figure 7, the strongest collaboration relationships belong to two groups of authors: the first pair includes C. L. Dunnaganand and M. T. Gallardo-Williams while the other group have three authors M. Abdinejad, H. S. Qorbani

Figure 5: The word cloud of the author's keywords illustrates words in various sizes depending on how frequently they appear.

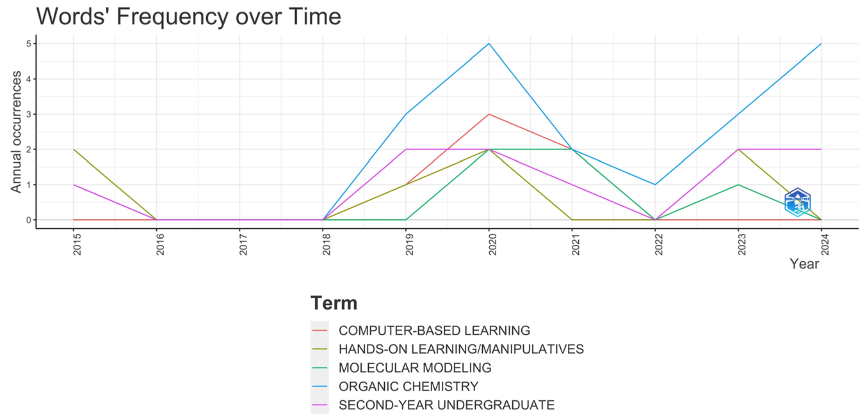

Figure 6: Mapping the word growth of the top 5 keywords based on the annual occurrence. Each keyword is denoted with an individual color to distinguish in the graph, which are respectively: Computer-based learning (Red), Hands-on learning (dark green), molecular modeling (light green), organic chemistry (blue), and second-year undergraduate (fuchsia).

and S. Dalili. Each group of the authors collaborated on 2 papers together in the dataset. The other authors connected in Figure 7, have only 1 article together.

3.8 Collaborative networks between countries

Vosviewer software was utilized to visualize the analysis of cooperation relations between countries, and the results are presented in Figure 8. Each country is signified by a circle, the size of which depends on the number of connections produced in that country. As indicated by the color blue, the USA is the most collaborative country in the dataset of this study; hence, given the largest circle. The curve linking the two circles denotes the cooperation between the two connected countries. The thicker the curve is, the stronger the cooperation between the two countries. For this analysis, the minimum number of articles for a country was determined as 1. The 3 clusters developed from 22 countries. The first cluster, the most crowded one, contained three countries (Argentina-Cuba-Switzerland). Clusters 2 and 3 had two countries inside. These coupled countries in these clusters are as follows, respectively; China-Saudi Arabia (Cluster 2); Poland-USA (Cluster 3).

3.9 Bibliographic coupling of countries

Figure 9 gives the bibliographic coupling of countries in the dataset. Bibliographic coupling of countries occurs when publications from two countries reference publications from a third country. It is a sign of the similarities between two countries working on a related subject matter. Bibliographic coupling is deemed to be strong or

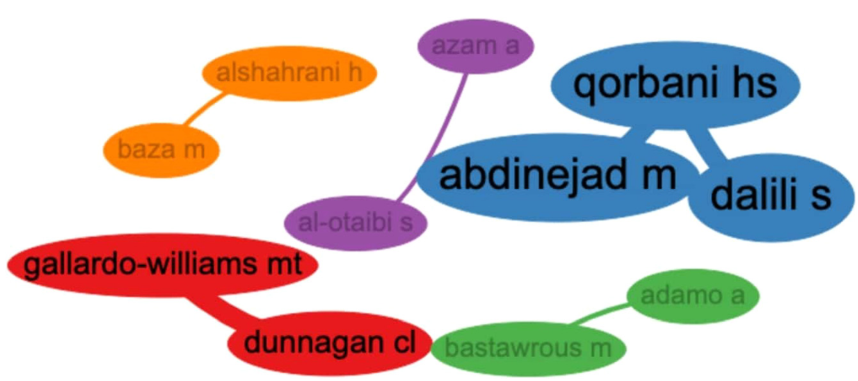

Figure 7: Co-authorship network map for showing the authors who co-wrote at least one article together with the thickest linkage showing the strongest collaboration relationships belong to two groups of authors.

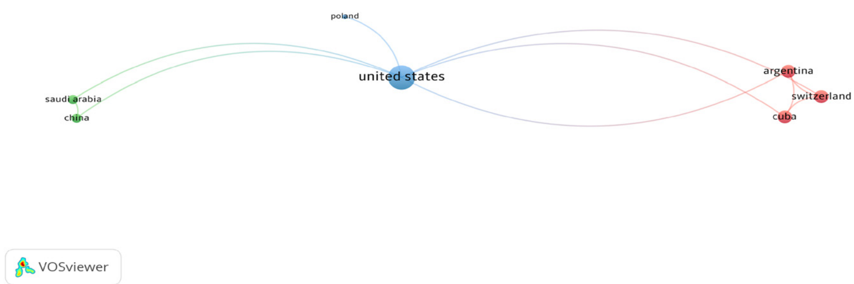

Figure 8: The co-authorship across all countries denoting each country by a circle, the size of which depends on the number of connections produced, connected by a curve denoting the cooperation between the two connected countries.

weak depending on the total number of references or citations of other third documents that they share. In Figure 9, the strength of the contributing countries is represented by the size of the blocks. The colors and proximity of the circles have been deliberately used to determine the clusters. Countries with a minimum of 1 document or more were included; 22 of 22 countries meet the criterion. Countries are clustered as one for their close relations in content; clusters' connections are categorized using quantitative network indicators. Bibliographic couplings of counties in the dataset were classified into 6 clusters. Argentina is placed along with Cuba, and Switzerland in cluster 1 (red cluster). Canada is in cluster 2 with Germany and Spain (green one). The United Kingdom, Portugal and Malaysia are in Cluster 3 (blue one). The United States, Poland and Italy are placed in Cluster 4. Moreover, Cluster 5 contains China and Saudi Arabia. Lastly, France is with Singapore in Cluster 6. Countries with the top bibliographic coupling action included the United States (288 total link strength); Argentina (159 total link strength); Cuba (159 total link strength) and Switzerland (159 total link strength). As shown in Figure 9, the United States has the largest network on the map, and it has the largest block. This means that it is the most productive country for related literature. The mapping analysis of bibliographic coupling of countries suggests that the USA is an influential contributor to IT-Organic Chemistry and that other countries are coupled to the USA.

3.10 Co-occurrence network mapping

With the Vosviewer program, "co-occurrence" and "author keywords" were chosen as the analysis unit. Then, when the minimum repetition count was selected as 2 for keywords, 29 keywords met this threshold. The network structure of the relationship between authors' keywords is presented in Figure 10. Each circle refers to a keyword. The size of a circle indicates the frequency of the keyword. Clusters of keywords are represented with different colors. Lines refer to co-occurrence links between keywords and the thickness of the line refers to the strength of the relationship between them. Five clusters were observed after the analysis. These clusters were composed of 4–9 keywords. The largest circle of each cluster indicates the dominant keyword. "Organic chemistry" (72 total link strength) for the green cluster, "Second-year undergraduate" (56 total link strength) for the fuchsia cluster, "Hands-on learning" (47 total link strength) for the red cluster, "Molecular modeling" (26 total link strength) for

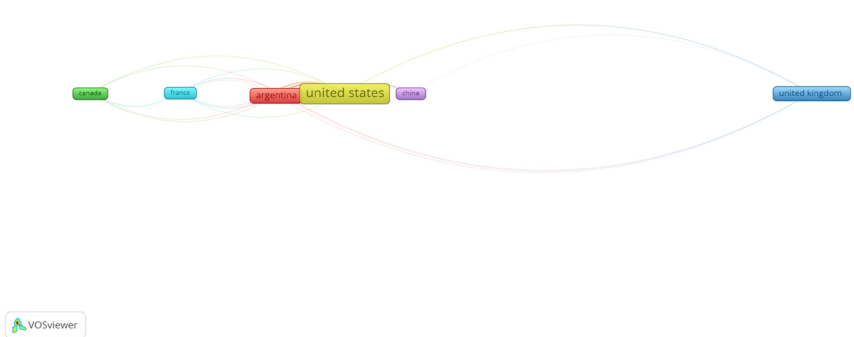

Figure 9: *Bibliographic coupling of countries divided into different cluster with regards to color and proximity in terms of references; their* strength is shown by the size of the blocks.

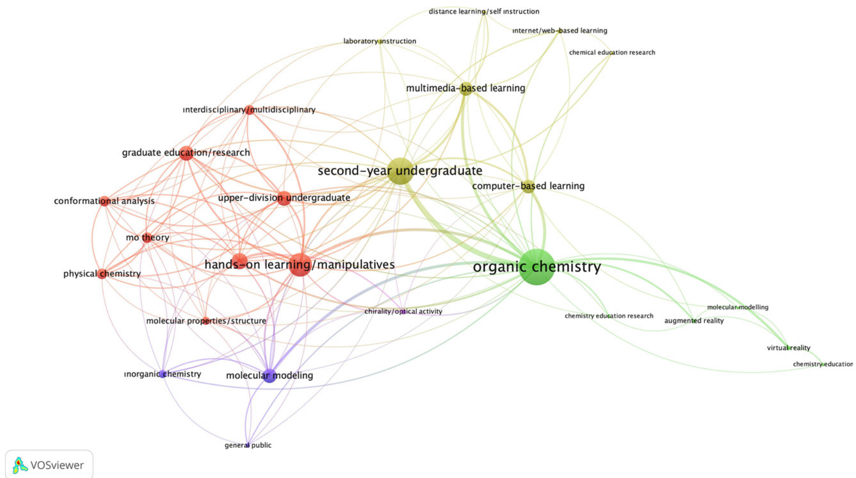

Figure 10: The co-occurrence of the authors' keywords represents circles referring to a keyword; and the size of a circle depends on the frequency of the keyword while the clusters of keywords are denoted with different colors.

the purple cluster, and "computer-based learning" (24 total link strength) for the blue cluster were the dominant keywords. The words "Organic chemistry", "Second-year undergraduate", "Hands-on learning", "computer-based learning", "upper-division undergraduate" and "molecular modeling" are situated at the center of Figure 10 because they have the highest connections with others.

4 Conclusion and recommendations

The results revealed that the first article that mentioned using innovative technology tools including "augmented reality" or "artificial intelligence" or "3D printing" or "virtual reality" in organic chemistry education appeared in 2014. This article was related to using 3D printers in teaching of structure–energy relationships in molecular conformations and in chemical reactions. When we investigated the descriptive statistics separately for each of the virtual tools included in the study, we found that 3D printers in organic chemistry were the oldest and most utilized tool. VR and AR followed 3D closely in organic chemistry education tools. When the average citations per document are compared, VR takes the lead, followed by AR and 3D printing studies. These citation values suggest that VR and AR studies will increase in numbers more quickly. Moreover, the document average age for AI is much lower compared to the others. However, a quick look at average citations per publication, co-authorships and international authorship would reveal that AI studies have already gained traction in organic chemistry education and will continue to do so.

Despite the first articles appearing in 2014, a considerable increment could only be seen after 2018. Especially for the period between 2019 and 2020, a more dramatic increase in using innovative technology tools in organic chemistry studies has been detected. There could be a wide range of reasons behind why the number of articles experienced a slow start only to upsurge later. At first maybe it was seen as difficult to implement innovative tools into the class environment. However, several pioneering studies on how to implement innovative technology tools like using 3D printers in organic chemistry classes encouraged more and more researchers to use IT in organic chemistry education. The drastic increase after 2020 has also been recognized by more recent studies on virtual tools-related science application (i.e., Authors 2). In a study investigating the virtual tools in Chemistry Education Research (CER) the main reason for this boost was found to be a direct impact of pandemic.

Results of the present study further indicate that the USA has had the most publications and had the highest citations in IT and organic chemistry-related articles. This might be because the other countries in the dataset started their publications later than the USA. In addition, the USA has the highest total link strength in the bibliographic coupling of countries in the dataset. This might also contribute to the leadership position of the USA in the dataset. Since some other countries started their publications much later than the USA and they had higher international co-authorship and average citations per publication, it is anticipated the number of citations per publication for these countries will increase further soon. Finally, it also appears that being a pioneer researcher and being published in an eminent journal is a useful way to become a distinguished author in the related field. Journal of Chemical Education was the most influential journal in the dataset as it has produced more than half of the articles in the database and its numbers are towering compared to the other journals that each published only one article on the topic. Moreover, Journal of Chemical Education was the first to have published an article in the database.

With regards to the recommendations of the study, we personally suggest that researchers interested in using IT in organic chemistry education follow the publications of the most influential authors and journals. The prospect of a wide-spread influence of the journal is a likely reason for authors to publish their papers in this journal rather than the other educational ones (Sozbilir & Teke, 2022). Acknowledging the most influential journals, authors, and countries can be a useful reference for researchers working on this topic. Moreover, being aware of conceptual (co-occurrences), intellectual (bibliographic coupling), and social (collaboration network) networks could help researchers to find a partner or fund for their project related to this area.

As this current study is one of the first researchers in a field on using IT in organic chemistry education, it will help the researchers in identifying the research trends and research gaps. As a result of the analysis, eight authors keywords stood out in terms of frequency which are “Organic Chemistry” “second-year undergraduate”, “hands-on learning”, “computer-based learning”, “molecular modeling”, “multimedia-based learning”, “upper-division undergraduate”, and “virtual reality”. All these findings and the research indicate that it is necessary to encourage scholars to research and integrate innovative technology tools into organic chemistry education. In this study, we focused on using some popular innovative technology tools such as augmented reality, virtual reality etc. Future research can broaden the scope of such trends to be inclusive of related aspects, such as virtual laboratories, eye-tracking technology, blended learning, e-learning etc.

5 Limitations

To begin with one of the limitations of this current study, it only focused on articles obtained from the Scopus database and was limited to the time until June 2024. Other data sources besides the Scopus database may be used in future studies. Furthermore, the bibliometric analysis in this study was not based on the detailed content analysis. This study is also limited to a correlational and quantitative nature. Future research may be supported with a core content analysis of bibliographic data. Also, the inclusion-exclusion criteria may have impacted the analysis results. Altered criteria may bring about a different perspective of the research area. Future studies may include other document types, such as proceedings. Furthermore, the total number of publications studied in this paper is limited and low due to the specific topic chosen. Thus, it is our suggestion for future bibliometric analyses to include the evolution of using IT tools in other disciplines related to the field of education to be included for a broader analysis of the investigating other present and future lines of research.

Research ethics: Not applicable.
Informed consent: Not applicable.
Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.
Use of Large Language Models, AI and Machine Learning Tools: None declared.
Conflict of interest: The author states no conflict of interest.
Research funding: None declared.
Data availability: Not applicable.

Appendix 1: Distributions of the articles in the scope of innovative technology tools used.

	Themes & titles	Year	TC[a]
	Virtual reality (VR)		
1-	Haptic virtual reality and immersive learning for enhanced organic chemistry instruction	2019	85
2-	Production and Evaluation of a Realistic Immersive Virtual Reality Organic Chemistry Laboratory Experience: Infrared Spectroscopy	2020	77
3-	Chemical Exploration with Virtual Reality in Organic Teaching Laboratories	2019	74
4-	Overcoming Physical Separation during Covid-19 Using Virtual Reality in Organic Chemistry Laboratories	2020	36
5-	Immersive VR for Organic Chemistry: Impacts on Performance and Grades for First-Generation and Continuing-Generation University Students	2021	15
6-	Vrchem: A virtual reality molecular builder	2021	10
7-	Design of virtual reality system for organic chemistry	2022	3
8-	Research on chemical reaction simulation platform based on animation model	2017	1
9-	A Roadmap to Support the Development of Chemistry Virtual Reality Learning Environments Merging Chemical Pedagogy and Educational Technology Design	2024	0
	Virtual reality (VR) & augmented reality (AR)		
1-	Opportunities and challenges of using immersive technologies to support students' spatial ability and 21st-century skills in K-12 education	2024	1
	Augmented reality (AR)		
1-	Student perceptions using augmented reality and 3d visualization technologies in chemistry education	2021	46
2-	A Simple and Practical Method for Incorporating Augmented Reality into the Classroom and Laboratory	2019	44
3-	Interacting with Three-Dimensional Molecular Structures Using an Augmented Reality Mobile App	2020	42
4-	MoleculARweb: A Web Site for Chemistry and Structural Biology Education through Interactive Augmented Reality out of the Box in Commodity Devices	2021	31
5-	Developing a Simple and Cost-Effective Markerless Augmented Reality Tool for Chemistry Education	2021	24
6-	Lessons learned: the use of an augmented reality application in organic chemistry laboratories	2024	0
	3D printing		
1-	Three-Dimensional (3D) Printing: A Straightforward, User-Friendly Protocol To Convert Virtual Chemical Models to Real-Life Objects	2015	58
2-	Illustrating Concepts in Physical Organic Chemistry with 3D Printed Orbitals	2015	45
3-	3D printers can provide an added dimension for teaching structure-energy relationships	2014	22
4-	Use of 3D Printing to Manufacture Document Camera Mounts in Support of Online Education Shifts during the Covid-19 Pandemic	2020	12
5-	3D Printing Workshop Activity That Aids Representation of Molecules and Student Comprehension of Shape and Chirality	2020	8
6-	Drawing in 3D: Using 3D printer pens to draw chemical models	2020	7
7-	Do-It-Yourself 5-Color 3D Printing of Molecular Orbitals and Electron Density Surfaces	2023	3
8-	Hydrophilic and Conductive 3D-Printed Electrocatalysts in Hydrogen Evolution Reaction for Undergraduate Experiments	2023	0
9-	The Approach to Aromatherapy and Essential Oils Extraction as a Generating Theme for Teaching Organic Chemistry	2023	0
	Artificial intelligence (AI)		
1-	Comparing Student and Generative Artificial Intelligence Chatbot Responses to Organic Chemistry Writing-to-Learn Assignment	2023	7
2-	Exploring the potential of AI-Chatbots in organic chemistry: An assessment of ChatGPT and Bard	2023	4
3-	A CASE (Computer-Assisted Structure Elucidation) for Bench-Top NMR Systems in the Undergraduate Laboratory for *de Novo* Structure Determination: How Well Can We Do?	2022	3
4-	Data Integration Method of Multi-source Feedback Evaluation for Remote Teaching Quality	2023	1
5-	ChatGPT Convincingly Explains Organic Chemistry Reaction Mechanisms Slightly Inaccurately with High Levels of Explanation Sophistication	2024	0

TC[a]: The total citations associated with these publications.

References

Abdinejad, M., Talaie, B., Qorbani, H. S., & Dalili, S. (2021). Student perceptions using augmented reality and 3D visualization technologies in chemistry education. *Journal of Science Education and Technology*, *30*, 87–96.

Aw, J. K., Boellaard, K. C., Tan, T. K., Yap, J., Loh, Y. P., Colasson, B., Blanc, E., Lam, Y., & Fung, F. M. (2020). Interacting with three-dimensional molecular structures using an augmented reality mobile app. *Journal of Chemical Education*, *97*(10), 3877–3881.

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*, *6*(4), 355–385.

Babak, S. (2020). Creating augmented reality USDZ files to visualize 3D objects on student phones in the classroom. *Journal of Chemical Education*, *97*(1), 253–257.

Börner, K., Chen, C., & Boyack, K. W. (2003). Visualizing knowledge domains. *Annual Review of Information Science and Technology*, *37*(1), 179–255.

Botero-Gómez, V., Ruiz-Herrera, L. G., Valencia-Arias, A., Díaz, A. R., & Garnique, J. C. V. (2023). Use of virtual tools in teaching-learning processes: Advancements and future direction. *Social Sciences*, *12*(70), 1–19.

Broyer, R. M., Miller, K., Ramachandran, S., Fu, S., Howell, K., & Cutchin, S. (2021). Using virtual reality to demonstrate glove hygiene in introductory chemistry laboratories. *Journal of Chemical Education*, *98*(1), 224–229.

Crowe, C. D., Hendrickson-Stives, A. K., Kuhn, S. L., Jackson, J. B., & Keating, C. D. (2021). Designing and 3D printing an improved method of measuring contact angle in the middle school classroom. *Journal of Chemical Education*, *98*(6), 1997–2004.

Dunnagan, C. L., Dannenberg, D. A., Cuales, M. P., Earnest, A. D., Gurnsey, R. M., & Gallardo-Williams, M. T. (2020). Production and evaluation of a realistic immersive virtual reality organic chemistry laboratory experience: Infrared spectroscopy. *Journal of Chemical Education*, *97*(1), 258–262.

Echeverri-Jimenez, E., & Oliver-Hoyo, M. (2024). A roadmap to support the development of chemistry virtual reality learning environments merging chemical pedagogy and educational technology design. *Journal of Chemical Education*, *101*(6), 2244–2256.

Edwards, B. I., Bielawski, K. S., Prada, R., & Cheok, A. D. (2019). Haptic virtual reality and immersive learning for enhanced organic chemistry instruction. *Virtual Reality*, *23*, 363–373.

Eriksen, K., Nielsen, B. E., & Pittelkow, M. (2020). Visualizing 3D molecular structures using an augmented reality app. *Journal of Chemical Education*, *97*(5), 1487–1490.

Evdokimenkova, Y. B., & Soboleva, N. O. (2020). Organic chemistry in Russia: Bibliometric publication flow analysis over the past 30 years. *COLLNET Journal of Scientometrics and Information Management*, *14*(1), 23–36.

Ferrell, J. B., Campbell, J. P., McCarthy, D. R., McKay, K. T., Hensinger, M., Srinivasan, R., Zhao, X., Wurthmann, A., Li, J., & Schneebeli, S.T. (2019). Chemical exploration with virtual reality in organic teaching laboratories. *Journal of Chemical Education*, *96*(9), 1961–1966.

Fidan, S., & Kasimi, Y. (2023). An investigation into artificial intelligence (AI) in the English as a foreign language (EFL) context. *International Journal of Educational Spectrum*, *5*(2), 269–280.

Gao, Y., Wong, S. L., Md Khambari, M. N., & Noordin, N. (2022). A bibliometric analysis of online faculty professional development in higher education. *Research and Practice in Technology Enhanced Learning*, *17*, 17.

García-Tudela, P. A., & Marín-Marín, J. A. (2023). Use of arduino in primary education: A systematic review. *Education Sciences*, *13*(2), 134.

Habig, S. (2020). Who can benefit from augmented reality in chemistry? Sex differences in solving stereochemistry problems using augmented reality. *British Journal of Educational Technology*, *51*(3), 629–644.

Hassan, N. M. H. N., Talib, O., Shariman, T. P., Rahman, N. A., & Zamin, A. A. M. (2022). A bibliometric analysis on how organic chemistry education research has evolved collaboratively over time. *Jurnal Pendidikan IPA Indonesia*, *11*(1), 73–90.

Kaya-Capocci, S. (2023). The new trends in entrepreneurship and STEM education studies: A bibliometric study. *İnönü Üniversitesi Eğitim Fakültesi Dergisi*, *24*(2), 869–892.

Kounlaxay, K., Dexiang, Y., Min, W. H., & Soo, K. (2022). Design of virtual reality system for organic chemistry. *Intelligent Automation & Soft Computing*, *31*(2), p1119.

Li, L. L., Ding, G., Feng, N., Wang, M. H., & Ho, Y. S. (2009). Global stem cell research trend: Bibliometric analysis as a tool for mapping of trends from 1991 to 2006. *Scientometrics*, *80*(1), 39–58.

Lin, T. C., Lin, T. C., Potvin, P., & Tsai, C. C. (2019). Research trends in science education from 2013 to 2017: A systematic content analysis of publications in selected journals. *International Journal of Science Education*, *41*(3), 367–387.

Maryasin, B., Marquetand, P., & Maulide, N. (2018). Machine learning for organic synthesis: Are robots replacing chemists? *Angewandte Chemie International Edition*, *57*, 6978–6980.

Mata, P. N., Martins, J. M., & Ferreira, J. C. (2024). New software product development: Bibliometric analysis. *Journal of the Knowledge Economy*, *15*, 1–24.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Annals of Internal Medicine*, *151*(4), 264–269.

Pala, F. (2023). Bibliometric map of digital storytelling studies conducted for education. *Balıkesir Üniversitesi Sosyal Bilimler Enstitüsü Dergisi*, *26*(49), 85–97.

Peiretti, F., & Bruner, J. M. (2018). Artificial intelligence: The future for organic chemistry? *ACS Omega*, *3*, 13263–13266.

Pence, H. E. (2020). How should chemistry educators respond to the next generation of technology change? *Education Sciences*, *10*(2), 34.

Pietikäinen, O., Hämäläinen, P., Lehtinen, J., & Karttunen, A. J. (2021). VRChem: A virtual reality molecular builder. *Applied Sciences*, *11*(22), 10767.

Pocan, S. (2023). Bibliometric analysis on digital game-based learning in mathematics education. *İnönü Üniversitesi Eğitim Fakültesi Dergisi*, *24*(1), 648–669.

Polat, H., Topuz, A. C., Yildiz, M., Taslibeyaz, E., & Kursun, E. (2024). A bibliometric analysis of research on ChatGPT in education. *International Journal of Technology in Education*, *7*(1), 59–85.

Prahani, B. K., Rizki, I. A., Suprapto, N., Irwanto, I., & Kurtuluş, M. A. (2024). Mapping research on scientific creativity: A bibliometric review of the literature in the last 20 years. *Thinking Skills and Creativity*, *52*, 101495.

PRISMA (2020). PRISMA endorsers. Available from: http://prisma-statement.org/Endorsement/PRISMAEndorsers [Accessed 5 May 2024].

Radu, C., Ciocoiu, C. N., Veith, C., & Dobrea, R. C. (2024). Artificial intelligence and competency-based education: A bibliometric analysis. *Amfiteatru Economic*, *26*(65), 220–240.

Renner, M., & Griesbeck, A. (2020). Think and print: 3D printing of chemical experiments. *Journal of Chemical Education*, *97*(10), 3683–3689.

Saleem, F., Khattak, A., Ur Rehman, S., & Ashiq, M. (2021). Bibliometric analysis of green marketing research from 1977 to 2020. Publications, 9, 1.

Scopus (2024). Available from: https://www.elsevier.com/products/scopus?dgcid=RN_AGCM_Sourced_300005030 [Accessed 5 May 2024].

Serrano-Ausejo, E., & Mårell-Olsson, E. (2024). Opportunities and challenges of using immersive technologies to support students' spatial ability and 21st-century skills in K-12 education. *Education and Information Technologies*, *29*, 5571–5597.

Sozbilir, M., & Teke, D. (2022). A bibliometric analysis of chemistry education research (CER) published in international journals (2001-2020): Status of CER in Turkey. 15th European Conference on Research in Chemical Education (ECRICE 2022), Rekhovot, Israel, 11–13 July.

Supplementary Material: This article contains supplementary material (https://doi.org/10.1515/cti-2024-0055).