Research Trends on Microscale Experiment Laboratory in Chemistry Learning: The Bibliometric Analysis of Literature

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Abstract. This research aims to summarize microscale chemistry experiments, encompassing scientific production, the most prominent researchers and countries involved, distribution trends over time, and the primary research areas. The bibliometric analysis of microscale experiments laboratory in chemistry was carried out using published documents, empirical research articles, review articles, and books published. In addition, about 213 articles and books published in internationally reputable journals were excavated from the Scopus database. Findings revealed that the number of articles on microscale experiments varied from 2010 to 2023. Meanwhile, collaborative co-authors mainly consist of researchers from the same country, and the countries involved in the collaboration are Asian, European, and American, respectively. Furthermore, there was a shift in research focus, where in the previous investigation, several examinations were carried out across disciplines, such as microscale experiments in chemistry, such as organic, inorganic, and physical chemistry. Although the current research focuses on integrating microscale experiments in chemistry learning, it has not been fully practiced among students or chemistry education students. Therefore, this may be an opportunity for further research that increases the implementation of microscale experiments into chemistry learning, especially for prospective chemistry teachers, to promote the attainment of education for sustainable development.

1 Introduction

Experimentation is an integral part of chemistry, and through experimentation, everyone can verify and/or find something new as an alternative solution to attract meaningful interest in learning [1]. However, the limited ability and cost of acquiring the tools and materials required for experimental activities in school and university laboratories are challenging. Therefore, the solution that can be proposed to this problem is to apply a microscale approach in chemical experiments [2].

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Microscale experiments are an alternative approach to overcoming problems associated with practical work, as they can provide hands-on activities and personal experiences for students using chemicals. In relatively small quantities, with small laboratory tools, safe, easy manipulative techniques, and high-quality skills [3]. Microscale chemistry emerged in the 1960s but did not develop at full speed until the 1980s [4]. Subsequently, it has been recommended for experiments in chemistry teaching laboratories because it has several advantages, including reducing (i) the amount of substance (there is an increase in safety for human health and the environment), (ii) reaction time (students' exposure to hazardous substances can be minimized), and (iii) the amount of waste (impact on the environment is minimized) [5,6].

Research on microscale chemistry experiments in the learning process in Tanzania [7], indicates that they facilitate a more engaging and enjoyable experimentation experience for most students. Furthermore, the experiments allow students to engage in self-directed experimentation, collaborate effectively with their peers, and communicate freely with their instructor. Moreover, it was indicated that students who accepted the implementation of this methodology exhibited enhanced scientific reasoning abilities when participating in group discussions and reflections during microscale experimental activities.

Experiments in chemistry are a potential medium for providing sustainability awareness that students must have during their learning process, both in the classroom and in the laboratory [8]. The microscale approach is a promising solution for generating chemical waste and its subsequent disposal, leading to an environmentally friendly concept [9,10]. In other words, literature on microscale experiments in chemistry is needed in learning practices that may prioritize environmentally friendly aspects. Therefore, it is essential to provide an overview of the most recent research in this field.

Therefore, an attempt is carried out to analyze investigation trends bibliometrically to draw important conclusions for further research [11]. This bibliometric analysis aims to identify trends in scientific output, leading authors and countries, a collaboration between authors and countries, and patterns of co-occurrence keywords in microscale experimental research in chemistry between 2010-2023. The identification of publishing and citation patterns can provide insight into the progression of research, while the analysis of the geographical distribution of publications can help identify regions with little coverage of pertinent research [12].

Bibliometric analysis is the most widely conducted literature research [13]. It focuses on the quantitative analysis of published data in databases, which can be used to generate objective findings [14]. Bibliometrics is the quantitative analysis of academic literature and its changes over time [15], especially in assessing and analyzing academic research conducted in various countries, universities, research centers, groups, and journals. In bibliometrics, two principal methods are employed for the exploration of research domains: performance analysis and scientific mapping [16,17]. Performance analysis is utilized to evaluate groups of scientific actors, including countries, universities, departments, or researchers, and assess their activities' impact based on bibliographical data.

Moreover, conducting bibliometric analysis will help researchers identify research objects and determine research focus [12]. Research that analyzes gaps from previous research using bibliometric analysis is not new. However, bibliometric analysis that reviews and analyzes the topic of micro-scale chemical experiments has not been widely conducted. Therefore, this paper is compiled to broaden the views of prospective micro-scale chemical experiment researchers to obtain comprehensive information. The identification carried out and research trends obtained from the bibliometric analysis results can be recommendations for future research that is interested in using this bibliometric method.

2 Method

This is a systematic quantitative literature research using bibliometric analysis, also called scientific mapping analysis, which spatially shows disciplines, fields, specializations, and individual documents or authors related to each other [18]. Bibliometric analysis is a statistical method for quantitatively analyzing data in scientific literature, research articles, conference articles, books, and other publications to prove and find the novelty and trends of a research [19,20]. It is also divided into five steps, namely, determining keywords, performing initial searches, refining searches, performing initial data statistics, and performing data analysis [21].

There are two main methods in bibliometrics, which are used to explore research areas that one wishes to explore, namely performance analysis and scientific mapping [16,17], which are the two methods used in this research. In this research, a data search was carried out using the Scopus database, which is one of the largest sources of scientific literature in the world [12,22,23]. Scopus updates its data every day with 32%, and therefore, it is considered accurate for bibliometric studies [24]. Furthermore, Scopus is one of the largest curated abstracts and citation databases with extensive global and regional coverage of scientific journals, conference proceedings, and books [22]. The reliability of the data in Scopus has led to its use as a bibliometric data source.

In this research, the standard scientific mapping workflow was adopted [16,17] as presented in Figure 1.

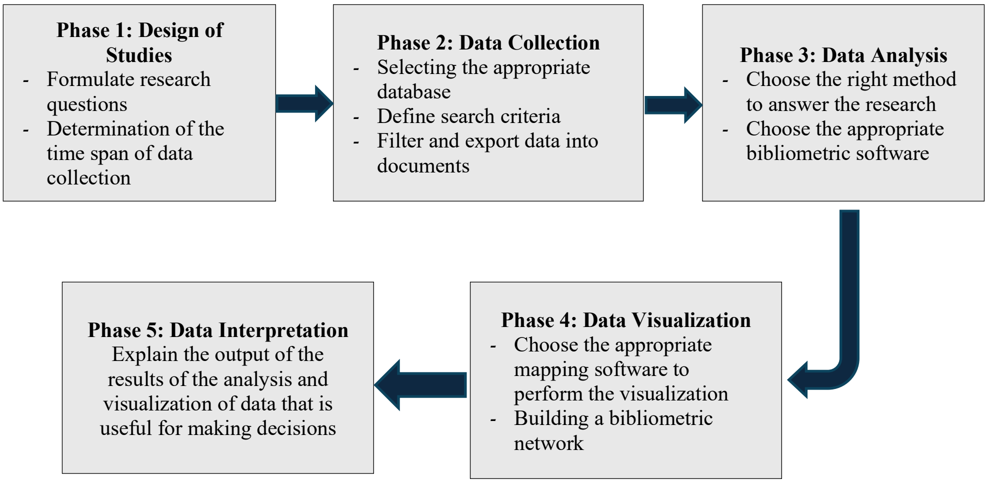

Fig. 1. Scientific mapping workflow using bibliometric analysis

2.1 Phase 1: Design studies

The website used for data collection was www.scopus.com, accessed on August 2023 to obtain bibliometric data. To direct the bibliometric research, four questions were formulated as follows (1) how to publish and cite research articles on microscale experiments in chemistry from 2010-2023; (2) Which authors and countries are most relevant in the publication of articles on microscale experiments in chemistry from 2010 to 2023; (3) Is there evidence of extensive collaboration between researchers and countries in microscale experimental research in chemistry from 2010 to 2023; and (4) What are the most relevant keywords and association patterns found in microscale experimental research in chemistry from 2010 to 2023.

2.2 Phase 2: Data collection

This research was conducted by searching the Scopus database engine with the keyword "microscale experiment on chemistry" from 2010 to 2023. There were 503 documents in the Scopus database; then limits were set based on the "area", namely "chemistry" and "social science", resulting in a total of 213 relevant documents used for analysis. These documents were exported in .ris or .csv format and then processed using VOSviewer software [25,26] and Microsoft Excel. Table 1 shows a summary of the data used for the bibliometric analysis.

Table 1. Summary of data extraction from Scopus and data used in bibliometric analysis from 2010-2023

Output	**Result**
Primary Information	
Duration 1	2010 - 2023
Total documents	213
Total document articles	207
Total document book chapter	2
Total document review	4
Total Sources (journals/book chapters/others)	84
Quotations total	3973
Average citations per document	18.65
Most productive country	United States
The author's country that produces the most published documents	China
The author's country that gets the most citations	United States
Single authors and collaboration authors	
Single authors of total documents	6
Co-authors of total documents	1154
Average co-author per document	5.45

2.3 Phases 3 and 4: Data analysis and visualization

Descriptive analysis (e.g. most relevant journals, author productivity, annual growth rate), content analysis (shared word analysis), and network analysis (collaborative co-authorship, keyword co-occurrence) were conducted to answer the research questions [27]. Two bibliometric analysis techniques were used; namely, performance analysis (including script analysis, year of publication, author, country, affiliation, etc.) obtained from the .csv metadata and then analyzed using Microsoft Excel for visualization [19]. Furthermore, scientific mapping analysis techniques use VOSviewer to visualize scientific mapping results [28], including networks based on keywords obtained through the .ris file metadata. Table 2 shows a complete summary of the data analysis software analysis tools. The scientific mapping analysis is summarized from some of the literature shown in Figure 1 [25,29].

Table 2. Summary of data analysis and software analysis tools

Research question	**Main method (actual analysis)**	**Science mapping tool**
What are the publications and article citations on micro-experimental research in chemistry from 2010 to 2023?	Performance analysis (analysis of the number of articles published per year and the average number of times an article is cited per document)	Microsoft Excel
What are the most relevant authors and countries that published articles on microscale experiments in chemistry from 2010 to 2023?	Performance analysis (identification of the most prolific authors, including scientific publications over time and most productive countries)	Microsoft Excel
Is there evidence of extensive collaboration between researchers and countries in microscale experimental research in chemistry from 2010 to 2023?	Science mapping (co-authorship analysis)	VOSviewer 1.6.18 version
What are the most relevant keywords and what are the association patterns found in microscale experimental research in chemistry from 2010 to 2023?	Science mapping (co-word analysis)	VOSviewer 1.6.18 version

2.4 Phase 5: Data interpretation

The interpretation in question explains the output of the analysis and visualization of data that is useful for making decisions or findings in the studies being studied. The position of interpretation is contained in the presentation of the results and discussion of this study, which was developed based on the research questions.

3 Results and Discussion

3.1 Development of scientific outcomes in microscale experiments on chemistry for the 2010-2023 period

When tracing documents based on the type from the Scopus database, it can be seen which kind of document is the most researched on chemical microscale experiments. Out of the 213 publications, there are three types of documents: articles, book chapters, and reviews. Figure 2 shows the number of publications based on the kind of document issued and shows that the highest number of publications is the type of article. This indicates that this research is interesting to be published in reputable articles and has a great chance of being published by this type of publication.

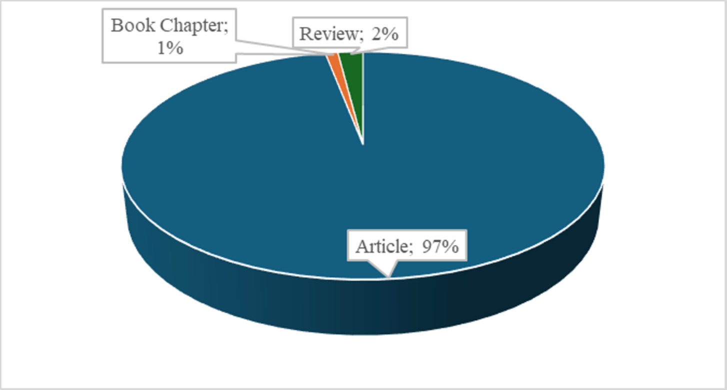

Fig. 2. Document types from 213 selected publications from 2010-2023

The development of research on experimental microscale from time to time during the 2010-2023 period shows fluctuations in the number of publications. In 2010 there were 7 publications, and this increased in 2011 (n = 10), 2012 (n = 15), and 2013 (n = 18). However, there was a decrease in 2014 (n = 14) and 2015 (n = 13). Then it increased again in 2016 (n = 17) but declined again in 2018 (n = 9). The highest number of publications was in 2019, with 24 publications. There was also a decrease in the number of publications in 2020 (n = 22), 2021 (n = 16), 2022 (n = 14), and 2023 (n = 13). Although not always increasing, the consistency in publications from 2010 to 2023 can be seen in the publication of scientific documents each year. Nevertheless, the consistency of research in this area is still maintained. The annual mapping of scientific production is shown in Figure 3. Thus, this can be a reference as an opening for research opportunities on microscale experiments in chemistry.

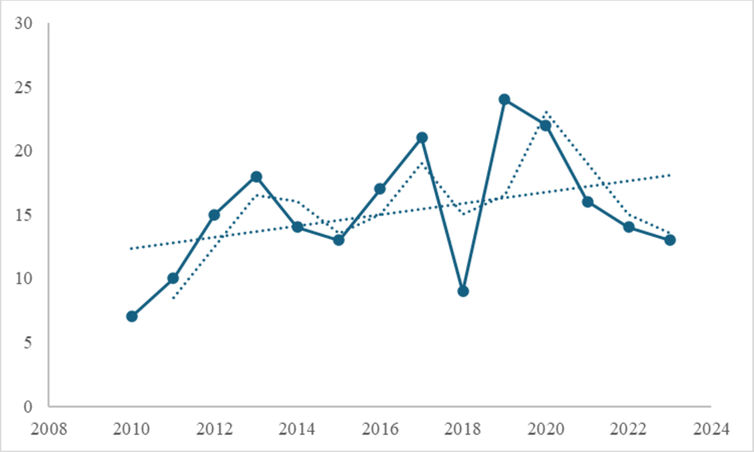

Fig. 3. Annual scientific production

Of the 1160 authors listed in the document, some are single authors and co-authors with other authors. Single authors produced 13 publications, while co-authors produced 200 other publications. The publications produced from 2010 to 2023 have been successfully cited 3973 times. Each published publication has cited an average of 18.65 times.

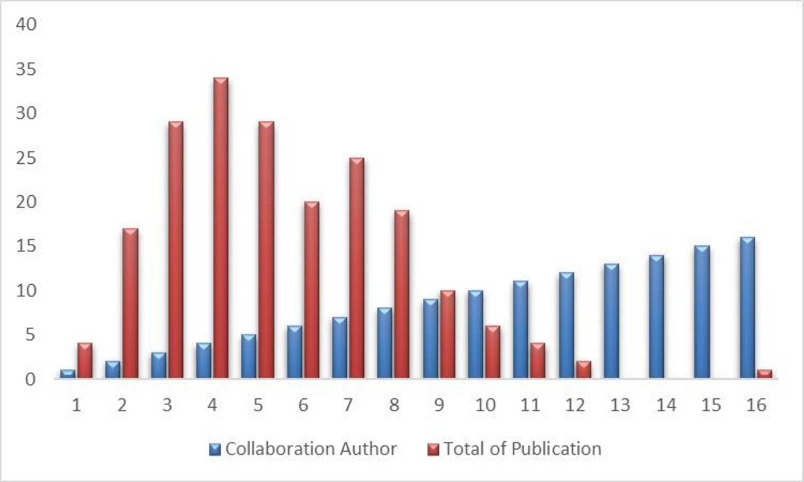

Fig. 4. Linkage of author collaboration with the total publications produced

Figure 4 shows a non-linear pattern between the number of authors involved in a publication document and the number of publications produced. The data shows that single authors produce more publications than a more significant number of authors. However, to comprehensively maintain the credibility and quality of research findings, a publication should be done in collaboration [30–32].

3.2 Authors and leading countries in publications on microscale ex-periments in chemistry for the 2010-2023 period

Further analysis focused on the most prolific authors in the field of microscale experimental research in chemistry between 2010 and 2023. Figure 5 shows the total publications of the top ten authors. With a total of 3 publications, Cai L. is the first author with the most publications from China.

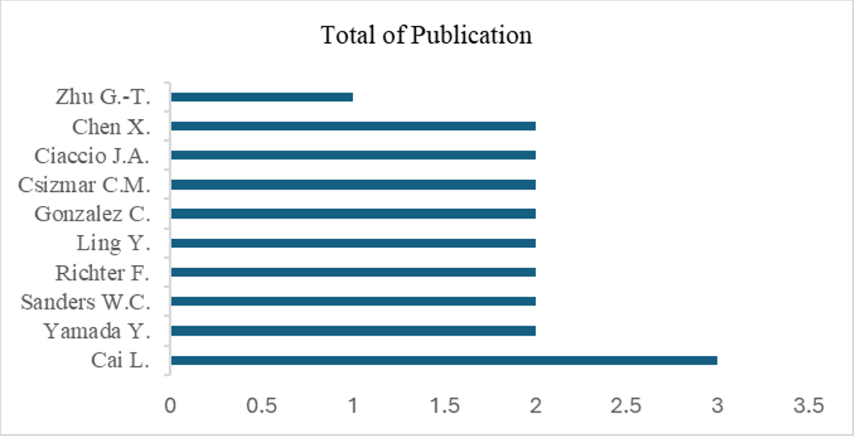

Fig. 5. Total of publications to the top ten first authors from 2010-2023

The three publications produced by Cai, L., are all published in the Journal of Chemical Education under the auspices of the American Chemical Society Publishers. The resulting publication document is relevant to the search carried out, namely about microscale experiments or microscale laboratories in the field of chemistry. Table 3 shows the top collaborating authors and their published documents.

Table 3. Collaborating authors by most published documents about "microscale experiment in chemistry"

Author's name	Publication source name	Total citation	DOI	Author keyword
Cai L., Wu Y., Xu C., Chen Z.	J Chem Educ, American Chemical Society (2013)	51	10.1021/ed300385j	Amino Acids; Analytical Chemistry; Applications of Chemistry; Food Science; Hands-On Learning/Manipulatives; Laboratory Equipment/Apparatus; Laboratory Instruction; Microscale Lab; Quantitative Analysis; Second-Year Undergraduate
Cai L., Zhang X., Luo L., Lin H., Chen J., Xu C., Zhong M., Liao X.	J Chem Educ, American Chemical Society (2019)	3	10.1021/acs.jchemed.8b00800	Analytical Chemistry; Hands-On Learning/Manipulatives; Microscale Lab; Quantitative Analysis; Upper-Division Undergraduate
Cai L., Ouyang Z., Huang X., Xu C.	J Chem Educ, American Chemical Society	3	10.1021/acs.scheme.9b01201	Green Chemistry; Hands-On Learning/Manipulatives; Microscale Lab; Quantitative Analysis; Upper-Division Undergraduate

Although the authors of the most published documents are from China, the United States produces the most published documents. Based on bibliographic data from the Scopus database, Figure 6 shows the countries with the highest number of publications, both single authors and collaborative authors, related to microscale experiments in chemistry from 2010-2023. The top authors are from Asia, the United States, and Europe.

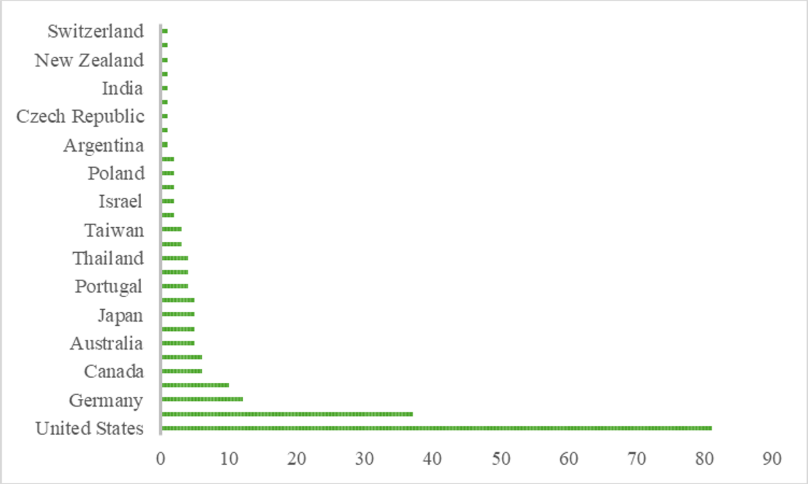

Fig. 6. The most significant number of publications countries (source of scopus.com with selected data, accessed in August 2023)

Specifically, the data shows no involvement of authors representing Asia countries, such as Indonesia (identifiable through the author's affiliation in published documents), in conducting microscale experiments in the field of chemistry, especially research documents or publications published in internationally reputable journals or publishers. Therefore, this can be an opportunity for authors representing Indonesia also to be able to participate in research on this topic, bearing in mind that there are many advantages of implementing microscale experiments, namely minimizing the use of substances, reaction exposure time, amount of waste, and reagent costs [33], to reduce the negative impact of chemicals on health and the environment [4].

3.3 Collaboration between authors and countries in microscale experimental research in chemistry for the 2010-2023 period

Scientific collaboration is one of the important drivers of research progress, supporting researchers in generating new ideas [34], scientific productivity [35], and academic quality [36]. Furthermore, it can support the transfer of knowledge and skills while minimizing typographical errors [34]. The number of joint publications can be an indicator of the amount of academic collaboration between researchers [37]. Therefore, a co-author analysis was performed to verify extensive collaboration, and the analysis results are visualized in Figure 7.

Based on scientific mapping analysis using VOSviewer, 16 clusters were obtained and marked with 16 colors. Different colors indicate the relationship between authors in the same published document. The visualization highlights the evidence of collaboration among researchers in microscale experiments in chemistry, even though most are composed of authors from the same country. The larger the form of the visualization, the more it shows the number of publications produced, both individually and in collaboration. Based on Figure 7, several visualizations of clusters appear to form a collection, indicating collaboration between authors, plus line visualizations that form a network that shows the relationship between authors within the same country and across countries.

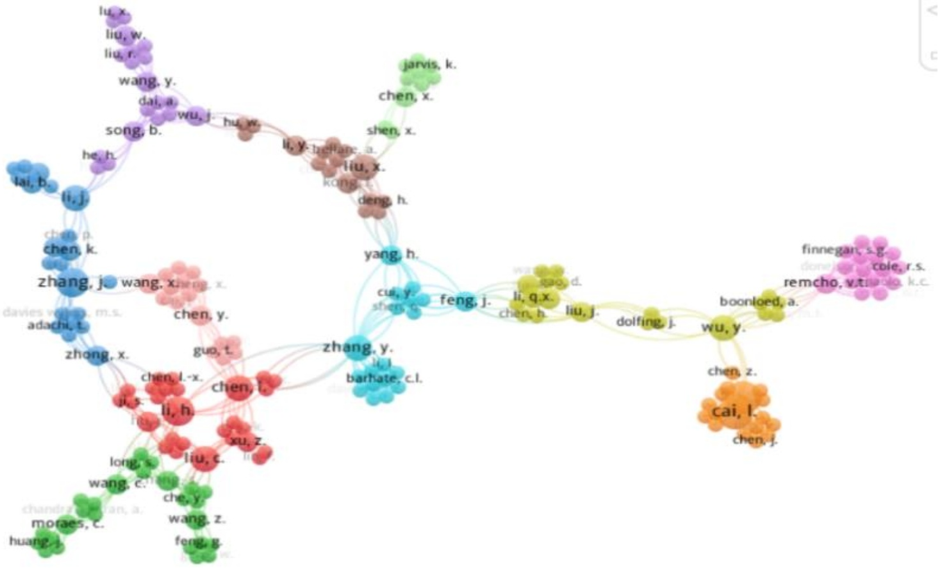

Fig. 7. The co-authorship network

Further clarification is needed to identify the most relevant published document for the research community on microscale experimentation in chemistry, i.e., by examining the number of times published documents have been cited by other authors from the same collection. Furthermore, the analysis results are presented in Table 4, which shows that Liu M et al. is the author with the highest number of citations, with a total of 544 citations. The publication produced in 2010 was in a journal with the abbreviated name Acc. Chem. Res.

Table 4. The ten authors with the most citations on microscale experiments during the 2010-2023 period

Authors	**Cited by**	**Country**	**Abbreviation name**	**DOI**
Liu M., Zheng Y., Zhai J., Jiang L.	544	China	Acc. Chem. Res.	10.1021/ar900205g
Kalcioglu Z.I., Mahmoodian R., Hu Y., Suo Z., Van Vliet K.J.	110	United States	Soft Matter	10.1039/c2sm06825g
Wang L., Liu W., Wang Y., Wang J.-C., Tu Q., Liu R., Wang J.	96	China	Lab on a Chip	10.1039/c2lc40661f
Yue Y., Zhang J., Wang X.	92	United States	Small journal	10.1002/smll.201101598
Carlson A.L., Bennett N.K., Francis N.L., Halikere A., Clarke S., Moore J.C., Hart R.P., Paradiso K., Wernig M., Kohn J., Pang Z.P., Moghe P.V.	91	United States	Nature communications	10.1038/ncomms10862
Ji Q., Li J., Xiong Z., Lai B.	88	China	Chemosphere	10.1016/j.chemosphere.2016.12.128
De Sousa L.R.F., Wu H., Nebo L., Fernandes J.B., Da Silva M.F.D.G.F., Kiefer W., Kanitz M., Bodem J., Diederich W.E., Schirmeister T., Vieira P.C.	86	Brazil	Bioorg. Med. Chem.	10.1016/j.bmc.2014.12.015
Lee K.S., Boccazzi P., Sinskey A.J., Ram R.J.	83	United States	Lab on a Chip	10.1039/c1lc20019d
Koesdjojo M.T., Pengpumkiat S., Wu Y., Boonloed A., Huynh D., Remcho T.P., Remcho V.T.	72	United States	J Chem Educ	10.1021/ed500401d
Anderson C.A., Jones A.R., Briggs E.M., Novitsky E.J., Kuykendall D.W., Sottos N.R., Zimmerman S.C.	71	United States	J. Am. Chem. Soc.	10.1021/ja4005283

3.4 Keyword co-occurrence pattern in microscale experiment research in chemistry for the 2010-2023 period

According to frequency analysis, the most frequently found keywords in published documents analyzed were "chemistry" (76 times), "microscales" (12 times), microscale lab (48 times), "laboratory instruction" (48 times), “first-year undergraduate” (22 times), “second-year undergraduate” (25 times), “upper-division undergraduate” (27 times), and “high school/introductory chemistry” (17 times). These terms are very broad and do not identify important research topics in the field or track changes over time. Therefore, a shared word analysis was carried out to uncover patterns of shared occurrences, which would allow a deeper perspective, as shared word analysis is generally capable of investigating the existing concrete content of the publication [38].

In other words, there is a thematic relationship between keywords when they often appear together [38]. Therefore, the terms of the publication title (article or book), abstract, and author's keywords are needed to obtain complete data. Using the VOSviewer software, 110 keywords were obtained, considered relevant to the search, and included in the mapping. The complete co-word network is visualized in Figure 8.

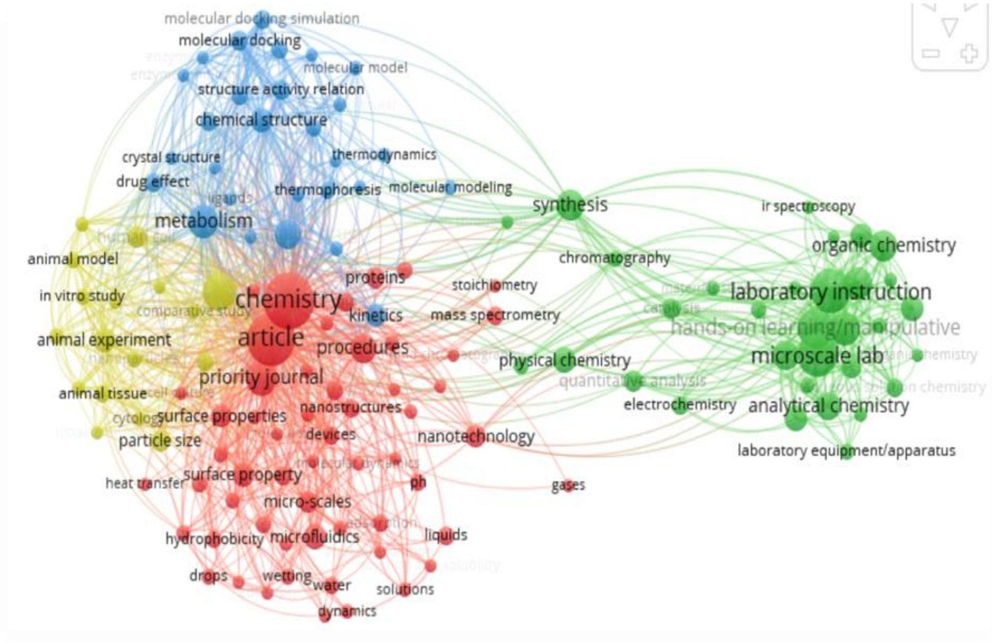

Fig. 8. Visualization of analysis based on co-word

In Figure 8, the font size represents the relative frequency of occurrence of the term, and the colored connecting lines represent the occurrence of the keyword. The term clusters that appear repeatedly are highlighted with the same color. Co-word analysis reveals five clusters. The clusters are represented in different colors, such as red (47 terms), green (31 terms), blue (29 terms), yellow (2 terms), and purple (1 term). Table 5 shows the relationship between the clusters and the terms that appear.

Based on the appearance of the terms obtained, the green cluster highlights the term "chemistry" and has a broader network because it is identified as a network with the other three clusters, although the terms involved are not more than the red cluster. Furthermore, based on the network formed, the green and red clusters are related to each other; for example, in the red cluster, there is the term "microscales", which is also related to the term "chemistry" in the green cluster. Figure 9 shows the network on the green cluster and the red cluster.

The blue cluster is identified as the cluster highlighting the term 'micro-scale laboratory'. This term forms a network with terms referring to issues related to learning at both secondary and undergraduate levels. Figure 10; the blue cluster; shows that "microscale experiments in chemistry" have the potential to be applied in learning, as evidenced by terms such as "high school/introductory chemistry", "first-year undergraduate", "second-year undergraduate", and "upper-division undergraduate". Although not much investigation has been carried out relating to this topic. Therefore, this can be a research opportunity to integrate the microscale experiment approach in chemistry learning at the secondary and tertiary education levels. The blue cluster shows that "microscale experiments in chemistry" have the potential to be applied in learning, as evidenced by terms such as "high school/introductory chemistry", "first-year undergraduate", "second-year undergraduate", and "upper-division undergraduate". Although not much investigation has been carried out relating to this topic. Therefore, this can be a research opportunity to integrate the microscale experiment approach in chemistry learning at the secondary and tertiary education levels.

Table 5. Clusters and emerging terms

Cluster	**Total terms**	**Term**
Red	47	Adhesion, adsorption, aqueous solution, biomolecules, cell culture, devices, DNA, drops, dynamics, electrochemical analysis, electrochemical technique, equipment design, fluorescence microscope, gases, high-performance liquid, hydrophilicity, hydrophobicity, ions, iron, **isolation and purification**, the limit of quantitation, liquid chromatography, liquids, mass spectrometry, methodology, **micro-scales**, microfluidic analysis, microfluidic analytical techniques, microfluidics, molecular dynamics, molecules, nanomaterial, nanostructures, nanotechnology, ph, polymer, polymerization, polymers, priority journal, procedures, proteins, scanning electron microscopy, **solutions**, stoichiometry, temperature, water
Green	31	Binding energy, biosynthesis, chemical analysis, chemical structure, **chemistry**, comparative study, crystal structure, dissociation constant, drug effect, drug effects, enzyme inhibitor, enzyme inhibitors, fluorescence, genetics, heat transfer, kinetics, ligands, metabolism, **microscale** thermophoresis, models, molecular, molecular model, molecular modelling, molecular structure, nanoparticles, particle size, structure-activity relation, thermodynamics, thermophoresis, ultrastructure, unclassified drug
Blue	29	**Analytical chemistry**, aqueous solution chemistry, catalysis, electrochemistry**, first-year undergraduate**, fluorescence spectroscopy, **green chemistry**, **hands-on learning, high school/introductory chemistry, inorganic chemistry**, **inquiry-based/discovery learning**, interdisciplinary/multidisciplinary, IR spectroscopy, **laboratory equipment**, **laboratory instruction**, material science, **microscale la**b, NMR spectroscopy, **organic chemistry**, oxidation/reduction, physical chemistry, problem-solving/decision making, quantitative analysis, reactions, **second-year undergraduate**, synthesis, **thin layer chromatography**, **upper-division undergraduate**, UV-vis spectroscopy
Yellow	2	**Chromatography**, high throughput screen
Purple	1	Electrophoresis

The bibliometric data analyzed in this study gives essential information, especially for chemistry education in the future, so that it can continue to be sustainable. One of the learning activities in education is experimentation. Experiments in chemistry are a potential medium to provide sustainability awareness that students should have during the learning process, both in the classroom and in the laboratory [8]. The microscale approach is a solution to minimize the formation of chemical waste that leads to the concept of environmentally friendly [9,10]. Besides being cost-efficient and safe, microscale experiments teach the importance of environmental responsibility and self-reliance in dealing with global issues, such as resource management and environmental conservation, which are aligned with education for sustainable development (ESD) principles [39].

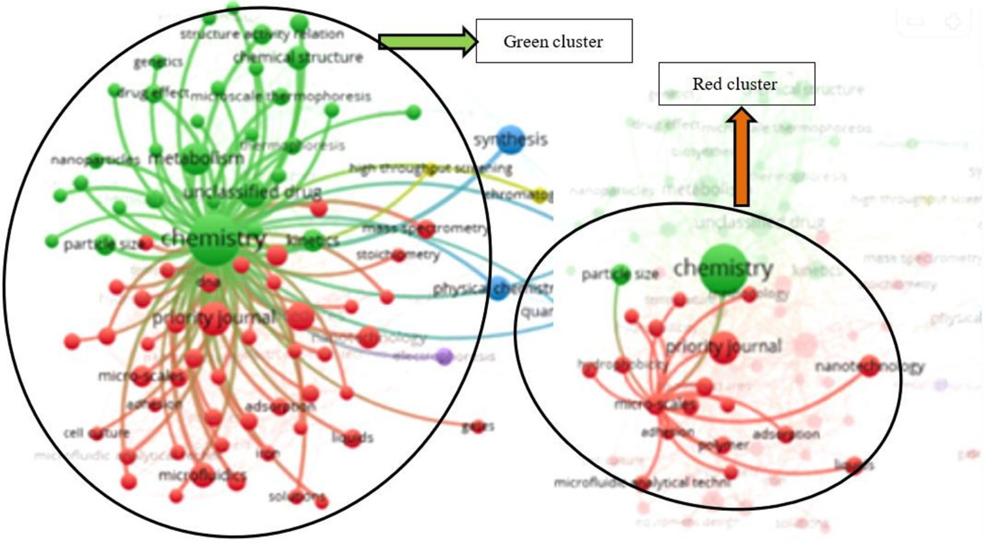

Fig. 9. Network on the green cluster and the red cluster

In other words, comprehensive literature on microscale experiments in chemistry is still very much needed in learning practices, especially in developing countries such as Indonesia. Educational policies in Indonesia also have goals that are aligned with ESD principles. Therefore, it is important to present an overview of recent research in this area to provide a comprehensive picture for the future advancement of chemistry education research.

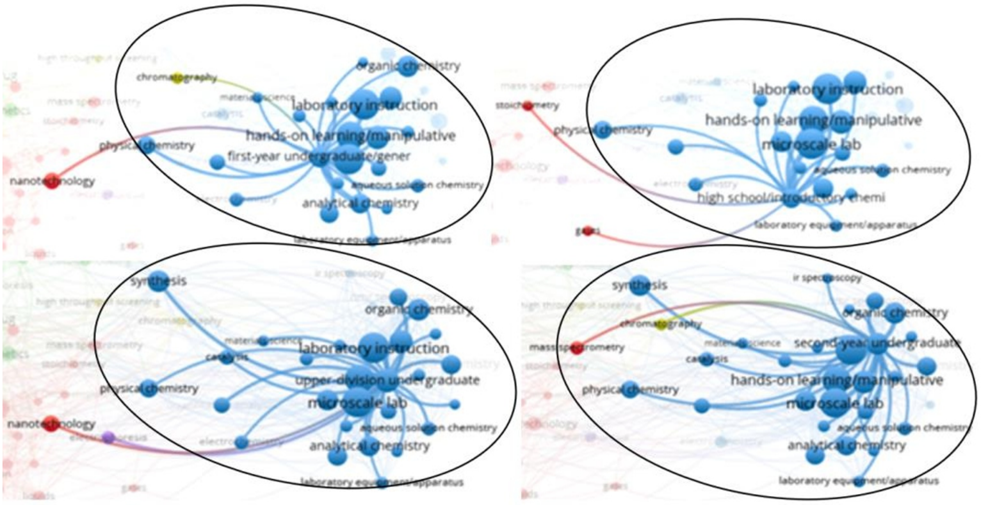

Fig.10. The network formed in the blue cluster according to the term chosen

4 Conclusions

In conclusion, the results of this study can contribute to future developments in microscale experimental research, particularly in chemistry. They can stimulate researchers in terms of research focus and co-authorship (collaboration). Furthermore, the literature on microscale experiments in chemistry has been the focus of this study, which aims to provide a vision that explains the current state of the scientific literature and publication trends over time. Based on the mapping analysis results, the potential for research or publication of microscale experiments in chemistry can be further developed in the chemistry learning process at both secondary and higher education levels. In conclusion, five research clusters on microscale experiments in chemistry are simultaneously visualized in the Scopus database. Geographical mapping shows that researchers from Asian, European, and American countries are authors collaborating on “microscale experiments in chemistry.” Meanwhile, researchers from China are the world's leading authors in quantity. On the other hand, the United States is the country that produces the most published documents related to “microscale experiments in chemistry”. Therefore, based on the findings of this bibliometric analysis, recommendations can be made to other countries to welcome research opportunities on microscale experiments in chemistry in secondary and higher education through collaborative research with researchers from several countries who have already focused on this topic.

Limitations

More academic articles were published regarding “microscale experiments on chemistry” during 2010-2023, compared to book chapters or reviews. The sample articles reviewed in this study can help researchers obtain valuable information to understand the direction of microscale experimental research in chemistry using bibliometric networks. However, various considerations should be noted before implementing these findings. Samples were taken only from the Scopus database; thus, a future review of other research databases could be conducted. In addition, this study only included articles published in English, so exploring articles in other languages may be an option for local researchers.

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