Macrothink Institute™

International Journal of Education
ISSN 1948-5476
2023, Vol. 15, No. 4

Integrating Virtual Reality Laboratories (VRLs) in Chemistry Education: A Systematic Literature Review

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Received: October 6, 2023 Accepted: December 16, 2023 Published: December 22, 2023

doi:10.5296/ije.v15i4.21372 URL: https://doi.org/10.5296/ije.v15i4.21372

Abstract

This systematic literature review investigates the importance of integrating Virtual Reality (VR) in chemistry education. It was discovered that only six countries are actively implementing and improving Virtual Reality Laboratories (VRLs) in chemistry education, with the United States (US) being the foremost country in research on VRLs. After 2021, there has been a significant surge in interest in the field, particularly through the Oculus system. Two specific topics that can be augmented by VR learning are laboratory safety and studying atomic and molecular structures. Unity 3D is the most widely used and accessible programming tool, and further studies are necessary to broaden the precise application of VR in chemistry education within the ASEAN and Malaysian settings.

Keywords: virtual reality, chemistry education, chemistry laboratories, VRLs, education

1. Introduction

Chemistry is a branch of science that uses precise terminology to describe the interactions and changes observed in real-world phenomena (Li et al., 2019; Trúchly et al., 2019). The interactions of the particles and the results of the experimentations allow for more elaborate explanations of the action mechanisms and interventional methods of nature and its surroundings (Karayilan et al., 2021). As a result, chemistry is required to solve everyday problems, and chemistry is used in many scientific disciplines. Learning chemistry requires both theory and practice (Lu et al., 2021). Experiments can improve learning motivation and practical abilities such as Science Process Skills (SPS) in dealing with abstract knowledge (Garduño et al., 2021; Prasetya & Ridlo, 2018). Experimental proficiency is especially important for Next-Generation Scientific Society (NGSS) members currently in school. They will need to use SPS at an advanced level when preparing for chemistry-related or interdisciplinary jobs (Fei et al., 2023). The purpose of experimenting is not to increase productivity but to provide practical experience in proposing and testing various hypotheses. As a result, chemistry laboratory practice curriculums are designed to cultivate logical and systemic thinking skills (Gungor et al., 2022).

The current era of education has embraced digital learning as the most sophisticated culture worldwide. Post-COVID-19 period has shown the need for digital and virtual learning as a mandatory strategy for students' dynamic learning (Iza Sazanita et al., 2022). Teaching and learning Science, Technology, Engineering & Mathematics (STEM) subjects such as chemistry which require the mastery of abstract knowledge through experimenting has been demanding a huge transformation in the learning entity (Mystakidis & Christopoulos, 2022; Trúchly et al., 2019). Thus, keeping the momentum of learning chemistry with the aid of virtual reality (VR) booming in the current era came into the frame as the Teach-Tech paradigm (Chan et al., 2021).

Before the era of Virtual Reality Laboratories (VRLs), Virtual Laboratories (VL) were in the frame of teaching and learning context as an option. Thus, it is important to know what VL is. VL are designed as interactive, digital simulations of activities that typically resemble physical laboratory settings (Mini Ratamun & Osman, 2018). The instruments, apparatus, tests, and procedures utilised in chemistry, biochemistry, physics, biology, and other academic fields are simulated in VL (Trúchly et al., 2019). At the same time, VRLs enable students to engage in lab-based learning exercises without incurring the costs and constraints of a physical lab. It can play an important role in institutional efforts to provide more diverse groups of students with access to lab-based subjects such as chemistry, as well as efforts to develop contingency plans for natural disasters or other disruptions to class activities, such as the COVID-19 pandemic (Eymur, 2019; Iza Sazanita et al., 2022; Sreekanth et al., 2022). For lessons, the risks of a mistake can be severe, and VLs shift that risk to the internet. VLs can offer more features and functions than physical laboratories in some ways, such as the ability to include quizzes and access to additional educational resources within the simulation. Currently, when VR is integrated into VLs, the student's experience and motivation tremendously increase in an individual learning context (Garduño et al., 2021; Prasetya & Ridlo, 2018).

Conventional teaching methods can meet students' needs for some areas of study, but they are not able to provide the best learning experience to every student in all subjects (Liu et al., 2017; Petersen et al., 2020; Rahman et al., 2021; Sreekanth et al., 2022). Virtual and real objects are combined in current VR technology. Experiments in virtual simulation can provide a visual 3D response (Kounlaxay et al., 2022; Rahman et al., 2021). As an outcome, students can observe the chemical mechanism at any time and from any location. This further improves learning outcomes and enhances interest in learning, enabling students to learn and develop their problem-solving and scientific process skills (EDUCAUSE, 2020; Ernawati & Ikhsan, 2021; Karayilan et al., 2021; Mystakidis & Christopoulos, 2022; Oladejo & Ebisin, 2021; Rasheed et al., 2021). To ensure safety, students can practice or be tested in virtual environments before performing actual laboratory operations.

Therefore, a systematic study was conducted to determine the recent studies on integrating VRLs into chemistry education. This systematic review aimed to provide solutions to the following questions:

- How many studies on VR Laboratory have been performed throughout the years 2018 to 2022?

- What topics in chemistry have integrated with VRLs?

- Which technological equipment and design tools are available for the development and use of interactive chemistry VRLs?

2. Method

2.1 The Review Protocol – PRISMA

This review was steered by Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA), which was developed by (Page et al., 2021). Striving for comprehensive reporting is crucial as it allows the reader to determine the relevance of the methodology used in the studies and, consequently, the reliability of the findings. In addition, outlining the characteristics of studies that contribute to a synthesis helps policymakers evaluate the significance of the results concerning their specific circumstances. Sierra-Correa & Cantera Kintz (2015) mentions that PRISMA has three clear advantages: 1) It establishes specific research questions that allow systematics study; 2) it establishes inclusion and exclusion set of criteria; and 3) it attempts to investigate a massive database of scientific literature within a specific time frame. Thus, the PRISMA methodology enables a comprehensive and detailed search for phrases related to futuristic teaching and learning. As indicated in Figure 1, this guideline comprises four phases: identification, screening, eligibility, and inclusion.

2.2 Systematic Searching Strategies

This study used four systematic strategies to identify relevant literature (identification, screening, eligibility, and inclusion). Thus, these selected articles can be effectively utilized in research by applying these strategies, resulting in a well-organized and transparent systematic literature review.

2.3 Identification

This study uses two major databases: Scopus and Web of Science (WoS). Scopus is an Elsevier theoretical and reference database that was launched in 2004. Scopus has almost 36,377 titles from approximately 11,678 content providers and 34,346 peer-reviewed journals in top-level subject fields, such as life sciences, social sciences, physical sciences, and health sciences. WoS is a subscription-based website that offers access to a variety of databases containing scholarly data. It was established by the Institute for Scientific Information and is currently owned by Clarivate Analytics. Table 1 shows the keywords used to find articles about VRLs in chemistry education.

Table 1. Keywords Used in the Search for Relevant Literature.

Databases	Keywords used
Scopus	TITLE-ABS-KEY (virtual AND reality AND laboratory AND stem AND education) OR TITLE-ABS-KEY (virtual AND reality AND laboratory AND chemistry AND education))
Web of Science (WoS)	virtual AND reality AND laboratory AND stem AND education (All Fields) or virtual AND reality AND laboratory AND chemistry AND education (All Fields) and Open Access and 2022 or 2021 or 2020 (Publication Years) and Article (Document Types) and Article (Document Types) and English (Languages)

2.4 Screening

The next procedure is screening. The publications that have been identified were 127 articles (Scopus) and 102 articles (WoS). These articles have been screened to be excluded from the research based on a few criteria (Table 2). Firstly, journals containing book series, books, book chapters, and conference proceedings were discarded. Consequently, the balance journals went through the screening process to limit the articles published between 2018 and 2022, referring to the concept of 'research field maturity' (Kraus et al., 2021), which means the last five years. Since the number of published articles was sufficient to conduct a fair representation analysis, this timeframe was preferred.

Furthermore, with the results obtained, the author decides only to analyse the empirical research publications written in English. With this step, 67 items remained excluded from 162 items since they did not meet the inclusion criteria. In the end, 57 items were judged to be evaluated based on the inclusion and exclusion criteria after 10 duplicate articles were eliminated.

Table 2. The Eligibility and Exclusion Criteria

Criterion	Eligibility	Exclusion
Literature type	Journal (research articles)	Book, book series, chapter in a book, systematic review articles, and conference proceeding
Language	English	Non-English
Timeline	Between 2018 and 2022	Before 2018

2.5 Eligibility

The screening procedure is followed by the eligibility process. The remaining research items were manually checked to observe if the recovered articles complied with the metrics. This step was done by reading the articles' titles, abstracts, and full texts. This procedure resulted in the exclusion of 49 articles because they did not focus on VRLs in chemistry education. Finally, this systematic literature review could potentially encompass only eight papers.

2.6 Included

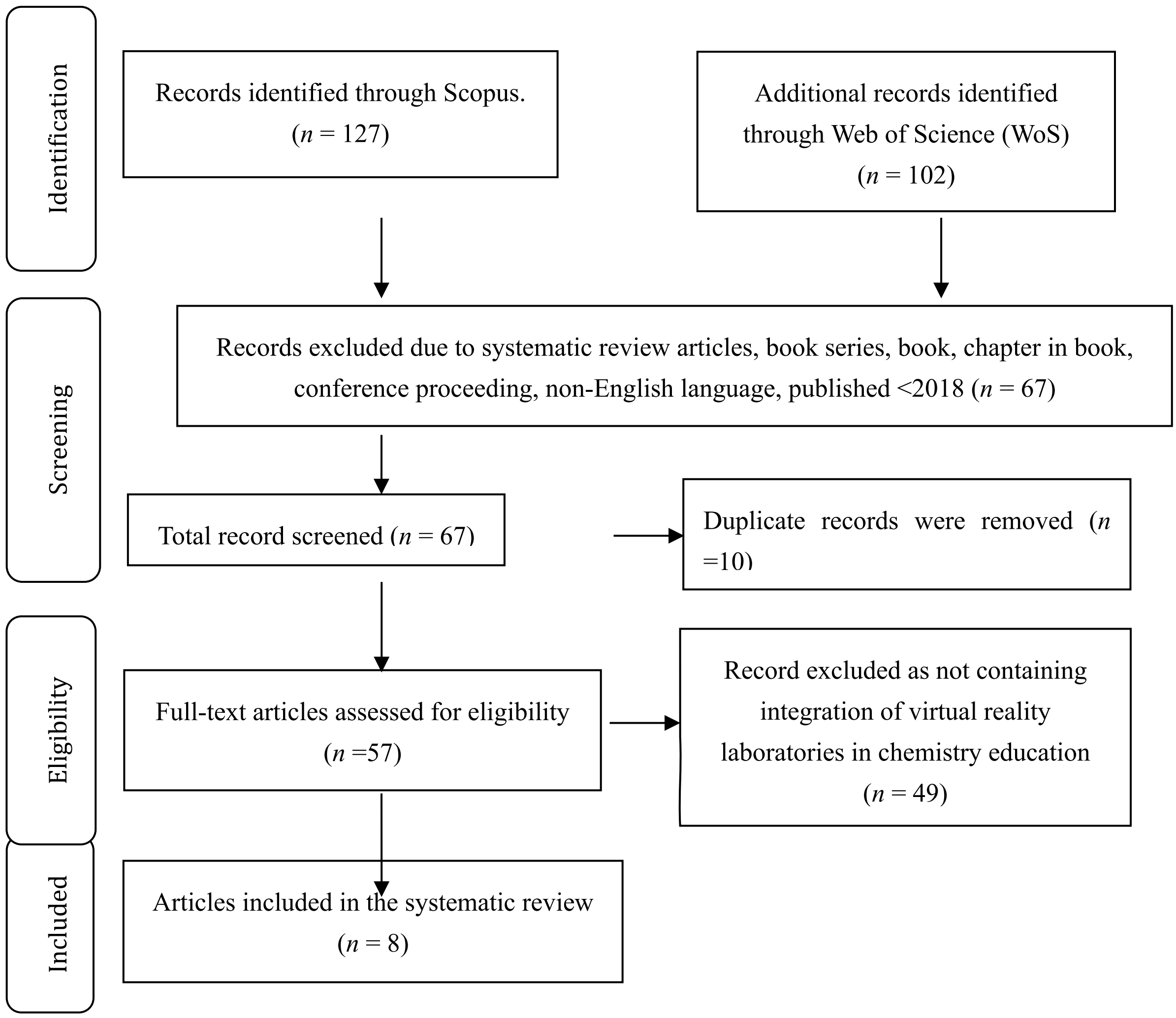

Figure 1. PRISMA Systematic Review Method, Adapted from Page et al. (2021)

The publications in this systematic review focused on integrating VRLs into chemistry education. Figure 1 was compiled using eight articles from the Scopus and WoS databases. These databases were selected for their quality publications, particularly in the field of education. All the study's objectives were related to integrating VRLs into chemistry education.

3. Results

3.1 VRLs in Chemistry Education by Publication Year

Understanding the publishing trend is a crucial factor in determining the progress of a particular field. In the years between 2018 and 2022, a large number of articles were published on promoting VRLs in chemistry education. To select the relevant articles, a systematic review was conducted, which led to the selection of eight articles. Figure 2 demonstrates the distribution of these articles year-by-year.

The graph shows an increase in articles on VRLs in chemistry education research from 2020, with no publications in 2018 and 2019. Interest peaked in 2021, with a slight decline in 2022. The number of publications focusing on integrating VRLs in chemistry education research was highest in 2021.

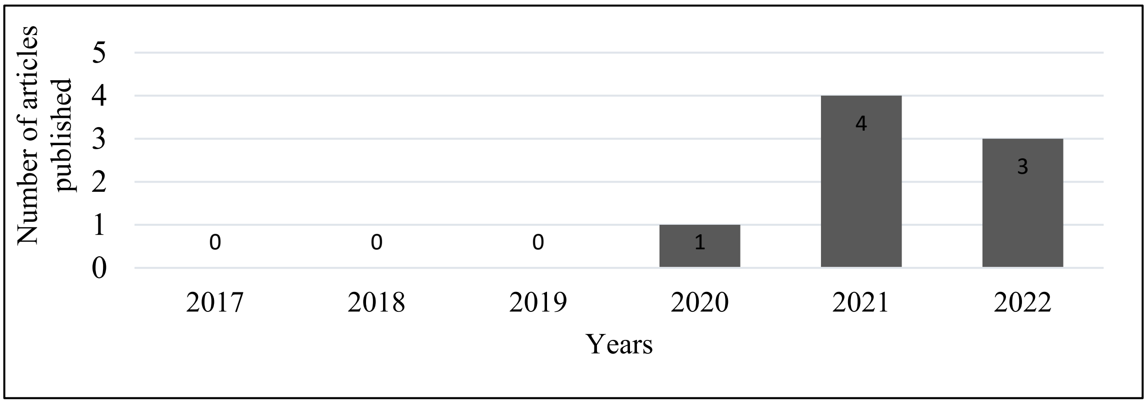

Figure 2. Distribution of the Number of Articles on Integrating VRLs in Chemistry Education from 2018 to 2022

3.2 Most Topics in Chemistry have been Integrated with Virtual Reality Laboratories

Chemistry consists of many subareas that have been learned at educational institutes. There were many articles published that generally mentioned chemistry. Hence, there is a need to analyse which topics have been adopting VRLs mostly, based on the articles finalised in this systematic review. Figure 3 shows the percentage of the topics of chemistry that have been integrating VRLs in the past five years.

The bar chart shows that most research was done in two subject areas, which are laboratory safety and atomic structure (including molecular structures). The other subject areas that have equally been concentrated are acid-base titration, chemical reactions in a general chemistry context, electrochemistry, and oxidation.

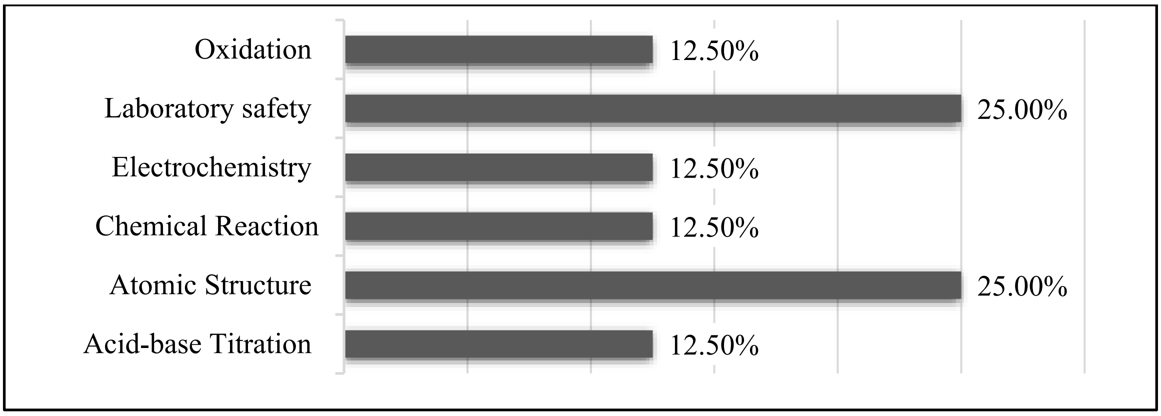

Figure 3. Percentage of Topics of Integrating VRLs in Chemistry Education

3.3 The Variety of Technological Equipment and Design Tools Available for the Development and Use of Interactive Chemistry VRLs

Based on the literature study, researchers discovered that various technological equipment and design tools had been used to develop interactive chemistry VRLs, as illustrated by Table 4. Table 4 consists of classification according to the eight articles finalised for this study.

The table shows that various technological equipment can be employed to integrate VRLs in chemistry education. From 2018 to 2022, the table covers the analysis conducted mostly using the Oculus system (50%). However, many other technologies are being utilized in chemistry VRLs' constructions, such as SimView system (12.5%), real-time system (12.5%), VR simulation (25.0%), Narupa XR (12.5%), and Google Chromecast (12.5%).

This literature review shows that Unity 3D is the most popular and user-friendly tool for VRL software development. Table 3 provides thorough information on all the technologies and design tools utilised in the eight articles in inclusion. The table also reveals that the leading county that has done more research on chemistry VRLs is the United States (US), and none of the ASEAN countries is involved with this study based on this literature review.

Table 3. The List of Technological Equipment and Design Tools Used in Chemistry VRL

No	Authors	Country	Technological Equipment	Design Tool
1	Gandhi et al. (2020)	New York, US	SimView System OOMD-blue Simulation	Unity 3D
2	Lu et al. (2021)	China	Robot, Real-time System	Unity 3D
3	Hu-Au & Okita (2021)	New York, US	VR simulation Oculus Head-mounted display Hand Controller HTC Vive	Unity 3D
4	Pereshivkina et al. (2021)	Russia	Narupa XR Javascript	GitLab
5	Broyer et al. (2021)	Idaho, US	Oculus Quest VR Headset	Unity 3D
6	Gungor et al. (2022)	Netherland	Oculus Quest Google Chromecast	Unreal 4 Engine
7	Sreekanth et al. (2022)	India	LED panel	Avatar-shell
8	Kounlaxay et al. (2022)	Korea	VR simulation Oculus head-mounted display Hand controller	Oculus Platform Unity 3D

4. Discussion

VR technology has shown immense potential in transforming various domains, including education. In recent years, integrating VR laboratories in chemistry education has garnered attention as a promising avenue to enhance learning experiences (Broyer et al., 2021; Eymur, 2019; Hu-Au & Okita, 2021; Wilkerson et al., 2022). However, despite the growing interest, it is important to critically assess the current state of VR laboratories in chemistry education. The analysis of the studies revealed that in the use and development of VRLs in chemistry education, the number of studies conducted in this area remains relatively low(Nersesian et al., 2019; Sreekanth et al., 2022). However, the potential benefits of VRLs in chemistry education are widely acknowledged (Duan et al., 2020; Kounlaxay et al., 2022; Nersesian et al., 2019; Sreekanth et al., 2022). The scarcity of research hinders our understanding of the efficacy and impact of VR laboratories on learning outcomes (Rahman et al., 2021). Only a handful of studies have investigated the use of VR in chemistry education, and even fewer have explored its effectiveness in comparison to traditional laboratory settings (Fussell & Truong, 2022; Mystakidis & Christopoulos, 2022; Nersesian et al., 2019). This limited body of research impedes the progress and wider adoption of VR laboratories.

Despite the paucity of studies, preliminary research suggests that VRLs can potentially enhance students' learning experiences in chemistry (Ernawati & Ikhsan, 2021; Kumar et al., 2021; Mystakidis & Christopoulos, 2022). VR enables students to engage in realistic simulations of chemical experiments, offering a safe and controlled environment for practical learning (Kumar et al., 2021; Motejlek & Alpay, 2022; Rasheed et al., 2021). Students can manipulate virtual equipment, observe chemical reactions, and analyse data, which enhances their understanding of complex concepts (Campos et al., 2022). Moreover, VRLs can facilitate interactive and collaborative learning experiences, enabling students to work together in a virtual space, regardless of their physical locations (Agbonifo et al., 2020; Garduño et al., 2021; Lu et al., 2021; Wijkmark et al., 2021). These are the efficacies that can be clearly obtained from the process of integrating VRLs in chemistry education.

However, the current evidence on the efficacy of VRLs is limited and inconclusive. VRLs have shown promise in various educational fields. Studies have indicated that VRLs can effectively improve students' conceptual understanding, laboratory skills, and motivation in biology education (Guldager et al., 2022; Nersesian et al., 2019; Prasetya & Ridlo, 2018) . They are particularly effective in teaching abstract topics such as cell and molecular biology, microbiology, genetics, and practical topics like dissection and biotechnology (Ernawati & Ikhsan, 2021; Prasetya & Ridlo, 2018). Additionally, VRLs offer benefits such as cost-effectiveness, accessibility, and the ability to conduct experiments with hazardous substances or infeasible conditions (Fussell & Truong, 2022; Sreekanth et al., 2022). However, the current evidence on the efficacy of VRLs is mixed. Some studies have not demonstrated significant effects on specific outcomes, such as drinking refusal self-efficacy in alcohol prevention (Guldager et al., 2022). Further research is needed to improve the effectiveness of VR Labs and explore their limitations in terms of experimental design and visualization. Studies comparing VR laboratories with traditional hands-on laboratories are scarce, and existing ones often have small sample sizes or lack rigorous experimental designs (Nersesian et al., 2019; Yang & Baldwin, 2020). Consequently, it is challenging to draw definitive conclusions about the superiority of VRLs in terms of learning outcomes, knowledge retention, and skill acquisition. Therefore, further research with larger sample sizes and rigorous methodologies is required to evaluate the true potential of VR laboratories in chemistry education.

In the aspect of technological constraints and implementation challenges, the implementation of VRLs in chemistry education is not without challenges. Technological constraints, such as the cost of equipment and the need for specialized software development, pose significant barriers to widespread adoption (Aljuhani et al., 2018; Altmeyer et al., 2020; Fussell & Truong, 2022; Nersesian et al., 2019). VR hardware and software advancements are necessary to improve the accessibility, affordability, and usability of VR laboratories. Moreover, integrating VRLs into the existing chemistry curriculum demands careful consideration (Gungor et al., 2022; Mystakidis & Christopoulos, 2022). The development of high-quality VR content that aligns with educational standards and learning objectives requires substantial effort and expertise. Chemistry educators need to be adequately trained to utilize VR laboratories and guide students through virtual experiments effectively (Mystakidis & Christopoulos, 2022). Additionally, infrastructure requirements, such as reliable internet connections and appropriate computer systems, need to be addressed to ensure seamless integration into educational institutions (Lu et al., 2021).

The findings of this article can be highly beneficial for chemistry educators who wish to integrate VRLs into their teaching. The study suggests that ASEAN countries have conducted the least amount of research in this area. This highlights the need for ASEAN nations to catch up to the rest of the world in terms of using VRLs as a tool to assist students in chemistry education. To achieve this, it is necessary to improve the training of teachers and educators, exposing them to the pedagogical techniques required to teach and train students using technological tools like VR. The analysis of the studies suggests that there is a growing interest among researchers in exploring the relationship between VRLs and the motivation of students in chemistry education. The number of studies on the integration of VRLs in chemistry education has increased significantly in recent years, contributing to this result.

5. Conclusion

This systematic review critically examines eight articles spanning the current 5-year study period, focusing on the technological equipment and design tools utilized in the integration of VRLs in chemistry education. Notably, a discernible trend emerges in the publication landscape, indicating a substantial increase in articles related to VRLs in chemistry education, particularly post-2021. This surge in scholarly output reflects a heightened recognition of the significance of VRLs in shaping contemporary chemistry education.

The observed uptick in research output can be attributed, in significant part, to the concerted efforts of a collaborative group of researchers from diverse geographical locations, including the United States, China, Korea, Russia, and India. These researchers have played a pivotal role in fostering advancements in VRL development and integration within educational contexts, with a particular emphasis on chemistry education. Their sustained contributions have established robust institutional frameworks dedicated to the exploration and implementation of VRLs in education, thereby contributing to the observed improvements in this domain (Ernawati & Ikhsan, 2021; Rahman et al., 2021).

A key finding from this systematic review is that Unity 3D is the most commonly used tool for developing virtual reality software for chemistry education. This suggests that Unity 3D is a popular and user-friendly platform within the academic community, and its wide adoption implies that it is an accessible and versatile tool for creating virtual reality content that caters to the diverse needs of educators and learners (Broyer et al., 2021; Gandhi et al., 2020; Hu-Au & Okita, 2021; Kounlaxay et al., 2022; Lu et al., 2021). However, the review also highlights a notable gap in the geographical distribution of research efforts. While the United States has emerged as a leader in researching virtual reality for chemistry education, there has been no involvement from ASEAN countries in this field. This underscores the need for greater research collaboration and participation from this region.

This systematic review highlights the increasing importance of VRLs in modern chemistry education. The collaborative efforts of researchers from different regions, along with the widespread adoption of Unity 3D, demonstrate the dynamic and cooperative nature of progress in VRL development. However, the limited representation of ASEAN countries in this field shows a need for greater global cooperation and knowledge sharing to ensure a more inclusive and comprehensive approach to integrating VRLs in chemistry education.

6. Recommendations

This study presents information on recent research on incorporating virtual reality laboratories (VRLs) into chemistry education. Based on the findings of this study, further research is needed to incorporate these findings. However, the implementation of VRLs in chemistry education is hindered by challenges related to technological constraints. In the future, research should focus on conducting well-designed studies with larger sample sizes to evaluate the true impact of VRLs on learning outcomes. Furthermore, efforts should be made to address the technological and implementation challenges to facilitate the integration of VRLs into the chemistry curriculum, ultimately improving chemistry education for students. Additionally, future research can be conducted using a more extensive database. This study aims to inspire future research to further enhance the integration of technology, especially VRLs, in chemistry education, particularly in Malaysia.

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Acknowledgments

We greatly appreciate the valuable contributions of the staff of the Faculty of Education, National University of Malaysia. We would also like to thank every team member who took the time to participate in this study.

Authors contributions

All authors have sufficiently contributed to the study and agreed with the results and conclusions.

Funding

This work was supported by the National University of Malaysia (GG-2023-007).

Competing interests

No conflict of interest is declared by the authors.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Macrothink Institute.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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