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Virtual Laboratories in Chemistry Education: A Systematic Review of Primary and Secondary Schools

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ABSTRACT This review aims to provide an overview of the use of Virtual Laboratories (VLs) in chemistry for basic education (CBE). The focus was on the context in which CBE was used and its effects on chemistry learning. Fifteen studies from Scopus, EBSCO-ERIC, and ScienceDirect were considered for the review. It was discovered that few perceived difficult topics were covered, with software insufficiently used. Further, only few studies focused on science process skills, while most studies were conducted at secondary school level. Key teaching approaches were applied in the studies, although others were noticeably absent. VLs were found to have a positive effect on achievement, motivation, self-efficacy, acquisition of knowledge, practical skills, self-directed learning, higher-order thinking skills, and social interaction, although nothing was reported on their effect on the components of the community of inquiry in the CBE. Recommendations are made.

Lay Summary

- Some reviews have been undertaken in chemistry education, but less in basic education.
- This paper reviews the contexts in which VLs are used in CBE.
- It also highlights how VLs have been used by chemistry teachers to implement different teaching approaches and to influence the learning process positively.

INTRODUCTION

It was through the pandemic that teachers, principals, and role players saw the advantages of online and blended learning platforms. Given that science is a hands-on subject, the situation may have been a mountain to climb. This highlights the importance of all the above-mentioned role players to move with time and not turn a blind eye to the evolution of technology and how it keeps one on their toes to move with its advancements. One of the ways in which science can be taught or performed in such a way that it does not lose its 'DNA' is through virtual laboratories (VLs). Despite learners losing their physical presence and direct contact through VLs (Winkelmann et al. 2014), they still have a number of advantages, such as enhancing learners' motivation and attitudes, as well as their conceptual knowledge and practical or laboratory abilities (Byukusenge et al. 2022). Similarly, Triejunita et al. (2021) found that VLs enhanced student learning outcomes, motivation, and involvement in the classroom. Additionally, VLs are available anywhere and at any time for the convenience of users (Triejunita et al. 2021). Consequently, teachers can assign tasks to learners to perform at home, individually or in groups, working at their own pace.

VLs are available in different formats and software. Widely known formats include virtual reality (VR), augmented reality (AR), and mixed reality (MR). VR is an interactive, multimodal, three-dimensional (3D) computer-generated simulation that allows users to explore or become fully immersed in a setting (Lai et al. 2022). Zhao et al. (2022) used it in chemistry education to simulate molecular structures in chemical reactions. Nonetheless, van Dinther et al. (2023) mentioned two types of VR, that is, non-immersive and immersive (IVR). With regard to the latter, the learners felt more as part of the environment, meaning the software immerses them in the environment, while the situation was opposite with regard to the former. The advantage of this reality is that it allows learners to enter sophisticated laboratories and use apparatuses that they may not be able to use in real environments.

Similar to VR, AR also plays a role in helping learners better understand complex chemistry concepts. For example, Abdinejad et al. (2020) highlighted how AR provides a three-dimensional (3D) representation of molecules, in contrast to the two-dimensional (2D) representation found in books, which may consist of limited information. As a result, through AR, learners are able to have a better understanding of chemical reactions and changes in molecules as they move from reactants to products. For instance, in the organic chemistry topic, learners can easily observe the structural adaptations of reactions through substitution, addition, and elimination reactions. In this review, the researchers looked at the types and formats of software in CBE.

Previous Reviews

Some reviews have been conducted on the use of virtual laboratories. For example, Chan et al. (2021) provided an overview of research on the use of VL and reviewed elements such as the types of technology used and the instructional design. They discovered that VL showed better results than traditional teaching methods, even though they showed greater effectiveness when blended with physical laboratories. The review also identified 3D desktop and VR as the dominant technologies, whereas inquiry-based learning, modality, and instructional scaffolding were identified as the emerging instructional design elements. This was also identified in the review by Mercado and Picardal (2023), who noted scaffolding and inquiry-based learning as the dominant instructional design components. Kartimi et al. (2022) reviewed bibliometric data of virtual laboratories in chemistry education from 117 articles searched through google scholar between the years 2011-2021. They identified topics such as chemical bonds, chemical equilibrium, and acid-base as the main topics in chemistry education on which VLs are built. However, his analysis was conducted at both high school and university levels.

Wang et al. (2024) selected 45 articles from 2001 to 2023 to review the VL trend in physics education. Their focus was on research contexts, technical features, instructional guidance, and effectiveness analysis. They found that VLs are mostly used in mechanics and electricity and are mostly applied to improve students' visual awareness. They also discovered that the experimental guidance methods differed at each school level and in traditional evaluation approaches. Byukusenge et al. (2022) reviewed the effectiveness of VLs, topics normally associated with their use, and their associated learning outcomes. From the 26 articles at the final stage of selection, it was discovered that VLs enhanced "students' conceptual understanding, laboratory skills, motivation, and attitudes" in the biology subject. They also highlighted and recommended VLs as secure and affordable tools. Sapriati et al. (2023) reviewed students' self-regulated learning (SRL) on the use of VLs. They utilised the PICO (Population, Intervention, Comparison, Outcome) framework. Moreover, they determined whether the components of SRL, such as cognitive, metacognitive, motivational, behavioural, and contextual strategies carried out by students, improved as a result of the use of VLs. Their interventions yielded a positive impact on student performance, and VLs create a positive arena for learning as they connect students' pre-existing knowledge with their experience, creating engaging social encounters. However, this review did not explore the elements of social presence experienced in the VL environment. Moreover, even though they explored the components of SRL, such as cognitive and metacognitive, they did not explore the element of cognitive presence. Other reviews were conducted on engineering and other non-education subjects. Nevertheless, apart from the second-order systematic review by Fadda et al. (2022), there are insufficient systematic reviews on the use of VLs in chemistry education at the primary and secondary/high school levels, which the author collectively refers to as CBE. This study aims to fill this gap by highlighting the progress made in the use of VLs in CBE.

Overview of Practical Work in Chemistry Education

One of the specific aims of the Physical Sciences curriculum is the "doing" of science (Department of Basic Education (DBE) 2011). The best medium for this is the laboratory through practical work. Of course, different apparatuses are required to undertake different process skills. The South African Physical Science curriculum identifies the skills of identifying and manipulating variables, developing models, hypothesising, classifying, communicating, measuring, designing an investigation, drawing and assessing conclusions, inferring, observing and comparing, interpreting, predicting, problem-solving, and reflective abilities (DBE 2011). However, some of these skills require sufficient apparatus to achieve them, which may prove to be difficult in isolated areas such as rural areas. As a result, teachers' are unable to facilitate inquiry-based approaches (Maponya and Kibirige 2019), which are key in practical work.

Furthermore, since the subject being dealt with is chemistry, some of the reagents are dangerous and may require additional personal protective equipment apart from a lab coat, such as goggles and gloves. Some reagents are corrosive and may require fume cupboards where they can be performed. As they are underprivileged, most rural schools cannot afford these resources. This is where virtual laboratories come into play. Therefore, schools would not be required to spend a lot of money (Vergara et al. 2020) to purchase more resources that should be used during the performance of sophisticated experiments.

Relevance of VLs in Chemistry Education

Despite learners losing their physical presence and direct contact with VLs, they carry several advantages, such as enhancing learners' motivation and attitudes, as well as their conceptual knowledge and practical or laboratory abilities (Byukusenge et al. 2022). Similarly, Triejunita et al. (2021) found that VLs enhanced student learning outcomes, motivation, and involvement in the classroom. Additionally, VLs are available anywhere and at any time for the convenience of users (Triejunita et al. 2021). Consequently, teachers can assign tasks to learners to perform at home individually or in groups, working at their own pace. Achuthan et al. (2018) used VLs in their study to come up with alternate conceptions and to address associated misconceptions. Through the use of 3D molecular visualisation and methodical synthesis of symmetric components, misconceptions about scientific ideas were significantly reduced. Moreover, there was an average 156 percent increase in learners' testing results. Likewise, Alhashem and Alfailakawi (2023) noted improved practical skills and interaction in chemistry physical experiments after learners were first exposed to VLs.

However, there are other components that are important in the learning of science, such as self-efficacy and motivation. Throughout the learning process, self-efficacy is essential for inducing behavioural changes that lead to improved performance (Kolil et al. 2020). VLs are one of the resources that improve learners' experimental self-efficacy and eliminate learners' experimental anxiety in chemistry education (Kolil et al. 2020: 1). Therefore, learners become motivated to perform virtual and physical experiments. VLs are also used by practitioners to effect conceptual changes. For example, Gunawan et al. (2019) used a VL to enhance the creativity and problem-solving abilities of their physics students. Chen et al. (2024), used guided VL to improve learners' process skills, which yielded positive results.

Another important aspect of learning is classroom engagement and interactions. Research shows a positive effect of VLs on learners' interaction and how that occurred at a convincing rate compared to face-to-face experiments (Nolen and Koretsky 2018). Hermansyah et al. (2019) used VLs to enhance learners' conceptual understanding of heat. Knowledge and understanding mainly lead to learners' achievement.

Purpose of the Study

This study intended to review the existing literature on VLs in the context of CBE. It focused on the context and the effect of VLs on CBE. Regarding the context, the focus was on countries of publications, years of publications, school level, software(s)/application(s)/format(s), chemistry topics, teaching approach, and science process skills. The researchers also checked the effect of VLs on achievement, motivation, self-efficacy, acquisition of knowledge, enhanced practical skills, self-directed learning, higher order thinking skills, social and teaching presence, and social interactions.

METHODOLOGY

A Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 was used in the study to select the relevant articles from three databases which were sought to achieve the study objectives (see Fig.1).

Search Criteria

The search was performed in databases such as Scopus, ScienceDirect, and ERIC as follows.

Scopus

The phrases used included "virtual laboratory*" AND "secondary school" OR "high school", which initially generated 207 results. Therefore, the search was reduced to 2014-2024 and produced 153 documents. The search was thereafter limited by ticking 'Social Sciences', 'Articles' and 'English' on the left menu, which led to 48 documents. The next step included selecting "virtual laboratory, virtual laboratories, students, simulations, high school/introductory chemistry, education, secondary education, STEM education, physics" under keywords and this generated 38 documents.

ERIC (EBSCO)

The initial results with the keywords "virtual laboratory" AND "secondary school or high school or secondary education" yielded 43 documents. with limiters such as 2014-2024. After ticking 'English' language, and 'full text', the database generated 42 articles.

Science Direct

This generated 21 articles after using the keywords "virtual laboratory" and "science education" AND ("secondary school" OR "high school"). This was after refining the search to the period of 2014-2024, research articles, and social sciences.

A total of 101 articles were retrieved from the three databases in the form of Excel and text. The records were then searched for duplicates, with approximately 13 duplicates found. Duplicates were deleted from the records, leaving 88 records.

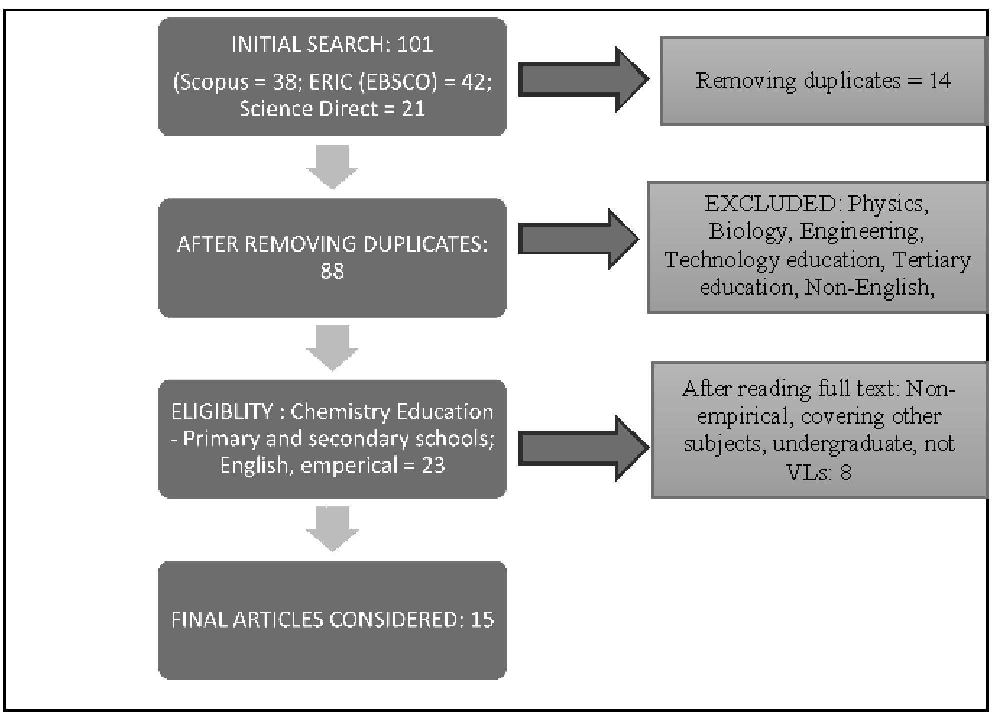

Fig. 1. Prisma Diagram

Inclusion/Exclusion Criteria

The records were then refined manually by checking eligibility through titles, abstracts, and keywords. Those who were not eligible were excluded due to factors such as (see Table 1):

- covering pre-service teachers, and
- focusing on other subjects such as Physics, Biology, Geography, Computer Science and Engineering or a combination of subjects.

This step led to 25 articles being considered for inclusion. The next step was to eliminate studies based on the type of paper and language. One article was not an empirical study, while another was not written in English, leaving the researchers with 23 studies. Through the reading of text, it was discovered that eight more articles should be removed, since one was a review paper, two were a hybrid of a review and empirical study, and one did not cover virtual laboratories but face-to-face laboratories. The other three articles were removed based on one representing Living things in Natural Sciences, while the other three focused on undergraduate students. Thus, 15 articles were included in the final stage of the review.

Extraction

Data were extracted by reading the Abstract, Introduction, Literature Review, Methodology, Results, Findings and Conclusion of the selected studies. The focus was on words or associated words including countries of publications, years of publications, school level, software(s)/application(s)/format(s), chemistry topics, teaching approach, and science process skills, achievement, motivation, self-efficacy, acquisition of knowledge, enhanced practical skills, self-directed learning, higher order thinking skills, social, cognitive and teaching presence (or community of inquiry) together with social interactions.

RESULTS

The results are presented in terms of the context and effects of the VLs in CBE.

Contexts of VLs in CBE

This section presents the contexts in which VLs were used in CBE. The focus is on the countries of publications, years of publications, school level, software(s)/application(s)/format(s), chemistry topics, teaching approach, and science process skills.

Year of Publication

The past decade has produced 15 publications covering VLs in the context of CBE (see Table 2). Four studies (25%) were published in 2014, followed by 2023 with three studies (S12, S13, S14). The former denotes an early stage of concentrated interest, possibly fuelled by developments in technology, whereas the latter may have come as a result of the pandemic, which led to several restrictions such as lockdowns, where practitioners were now seeking alternative forms such as the use of VLs. The remaining years produced one study each (S6, S7, S8, S9, S10, S11, and S15) (see Table 1), with the exception of 2017, which did not produce even a single study. This demonstrates a decline in the interest of VLs in CBE as the period moves to before the pandemic. Meanwhile, the pandemic period (2019-2022) only produced four studies at a rate of one per year (S8, S9, S10, and S11), in a period where one would expect a higher number of publications, given the issues of lockdown and remote learning where learners did not have the luxury of face-to-face interactions with their teachers and fellow learners. However, as indicated above, the consequences of the pandemic were noted in publications from 2023.

Table 1: Inclusion and exclusion criteria for the review selection stage

Exclusion	*Inclusion*
Non-English papers	English
Review or combined review and empirical	Empirical studies
Conference papers, grey literature or other forms which are not journal articles	Journal articles
Biology, Physics, Engineering, Technology education	Chemistry education
Tertiary institutions	Primary and secondary schools

Countries of Publications

Only six countries (Slovenia, China, Nigeria, Taiwan (twice), and Tanzania (twice)) could be located from the text of the studies (S1, S3, S7, S9, S10, S11, and S12, respectively (see Table 2). While the country of publications could not be traced from the text of the rest of the other studies. This restricted geographic distribution implies that VL research in CBE is still being driven by particular research teams or regional educational issues rather than being a global phenomenon.

School Levels

Only two studies were conducted at the primary school (PS) level, while 13 studies were conducted in the high school (HS) context (see Table 2 and Fig. 2). This again exposes a gap in the VLs in chemistry for primary schools.

Table 2: Year of publications and study codes for CBE VLs

Year	*Studies*	*Study codes*	*School level*	*Country*	*Type approach*	*Topic*
2014	Herga et al. (2014)	S1	L P	Slovenia		
	Scherer and Tiemaan (2014)	S2	HS	Not specified from text (NSFT)	Problem solving	Reaction Yield
	Cai et al. (2014)	S3	JHS	China	Inquiry based learning	
	Winkelmann et al. (2014)	S4	HS	NSFT	Expository teaching style	Rates of Reaction
2015	Hale-Hanes (2015)	S5	HS	NSFT	Open inquiry	
2016	Herga et al. (2016)	S6	PS	Slovenia	NSFT	State of Matter; Chemical Reaction; Illustration of Gaseous Particles; Compounds; Separation of Substances from a Mixture; Physical and Chemical Changes of Matter
2017						
2018	Gambari et al. (2018)	S7	SHS	Nigeria	Collaborative learning	Introduction to Qualitative Analysis; Identification of Cations and Anions
2019	Wolski and Jagozinski (2019)	S8	Both	NSFT	NSFT	NSFT
2020	Hung and Tsai (2020)	S9	LHS	Taiwan	Meta-cognitive scaffolding strategy	Specific Heat
2021	Amin and Ikhsan (2021)	S10	SHS	Indonesia	NSFT	Chemical Equilibrium
2022	Lai et al. (2022)	S11	JHS	Taiwan	Inquiry based	NSFT
2023	Manyilizu (2023a)	S12	SS	Tanzania	NSFT	NSFT
	Manyilizu (2023b)	S13	SS	Tanzania	NSFT	NSFT
	Yakob et al. (2023)	S14	HS	NSFT	NSFT	Acid-Base; Substance Purification; Chemical Reactions; Stoichiometry; Thermochemistry
2024	Fitriyana et al. (2024)	S15	SS	NSFT	NSFT	NSFT

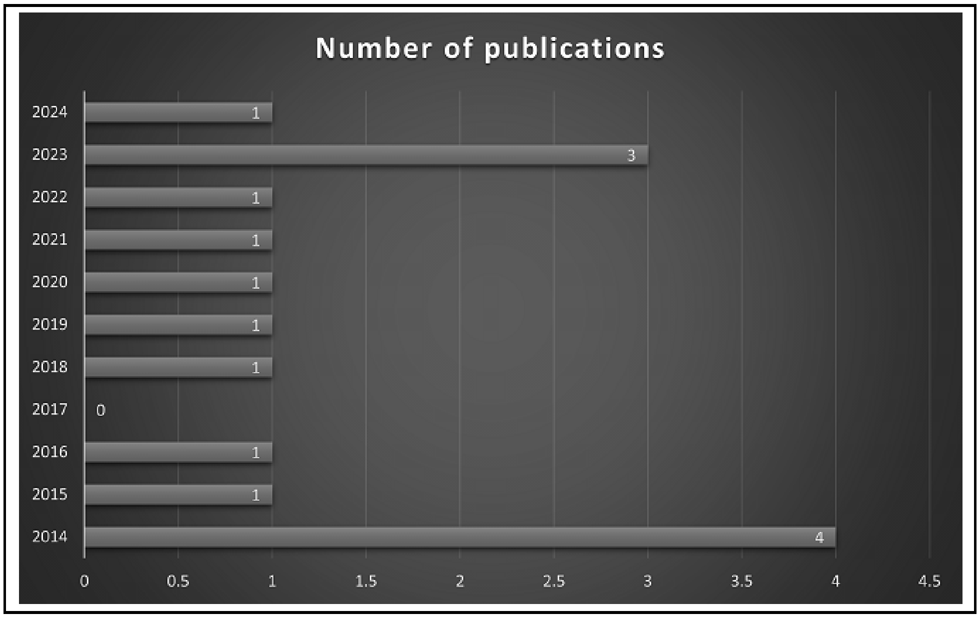

Fig. 2. Number of publications per year from 2014-2024

Nonetheless, one study (S8) involved learners from both PS and HS levels. Of the two PS studies, one was conducted in lower primary (LP) (S1), while there was no specificity with the other (S6). For the 13 studies conducted at the HS level, three were at junior/lower high school (JHS/LHS) (S3, S9, S11), two (S7, S10) at senior (HS) level, and there was no specificity with the other seven studies (S2, S4, S5, S12, S13, S14). The high rate of studies at the high school level compared to the primary level demonstrates a missed opportunity to look into how early virtual experiences can develop a fundamental spatial and procedural understanding of matter.

Software(s)/Application(s)

Different software programs were used in different studies, with some appearing in more than one study. For example, Virtual Chemical Laboratory Crocodile Clips Chemistry, Second Life (SL), and Chemistry Virtual Laboratory (CVL) appeared in two studies each (see Table 3). The remaining software programs, namely, Kinect for

Table 3: Software programs/applications together with their modes

Software/Application	*Mode (VR or AR)*	*Number of publications*	*Publications*
Kinect for Windows SDK	NSFT	1	S8
Virtual Chemical Laboratory Crocodile Clips Chemistry	VR	2	S1; S6
Second Life (SL)	NSFT	2	S4; S10
VICH-Lab	NSFT	1	S15
Scientific Investigation Lab (SIVRLAB)	VR	1	S11
Chemistry Virtual Laboratory (CVL)	NSFT	2	S7; S12
Interactive Data Modelling System (IDMS)	NSFT	1	S9
Java enabled Software	AR	1	S3
PhET Interaction Simulation Application	NSFT	1	S14
No clarity on software used	NSFT	3	S2, S5, and S13

Windows SDK, VICH-Lab, Scientific Investigation Lab (SIVRLAB), Interactive Data Modelling System (IDMS), Java-enabled software, and PhET interaction simulation application, appeared in one study each. This variation highlights the lack of a single predominant platform for VL research in the CBE. However, there was no clarity on S2, S5, and S13 regarding the software used, exposing the methodological limitations of these studies. Furthermore, regarding the issue of VR and AR, only one study covered AR, while two studies covered VR. Nonetheless, this shortcoming underscores the need for more empirical studies covering all the three types of realities – AR, VR and mixed realities (XR).

Kinect for Windows SDK

Wolski and Jagozinski (2019) applied the Kinect for Windows SDK in their study. The software can recognise the user's motions and gestures, which in this study were hand movements in the virtual chemical laboratory. Furthermore, the software allows users to simulate the experiment in real time, such as by selecting the apparatus and mixing substances (Wolski and Jagozinski 2019). This places it closer to an immersive, bodily engaged experience and highlights the research interest in incorporating haptic and kinesthetic feedback into VLs.

Virtual Chemical Laboratory Crocodile Clips Chemistry

The Virtual Chemical Laboratory Crocodile Clips Chemistry was used in two studies, namely, Herga et al. (2014) and Herga et al. (2016). Not only is the software recommended by teachers universally (Herga et al. 2016), but it also allows learners to work individually or in groups, following the interface's progressive step-by-step instructions as they navigate the virtual experiment (Herga et al. 2014). The software also has a safe way of displaying experiments and acts as a tool for teachers to do so while using a frontal teaching approach through an interactive whiteboard (Herga et al. 2016). This innovative integration presents an opportunity for learners to interact with the virtual world in diverse ways. In Herga et al.'s (2016) study, the software was used to demonstrate to grade 7 learners topics such as the concept of pure substances and compounds and substances at the sub-microscopic level. The sub-microscopic level deals with objects that cannot be seen with the naked eye to provide a better understanding. Through the manipulation and exploration of virtual representations of abstract concepts, this creative and interactive technique improves learners' conceptual understanding.

Second Life (SL)

According to Winkelmann (2013), SL is the most widely used virtual environment for education purposes. It was applied in studies by Winkelmann et al. (2014) and Amin and Ikhsan (2021). In the former study, students performed a simulated experiment that involved the flow of hydrogen through tubing connected to a graduated cylinder and an upside-down beaker placed in a certain version of a water bath. Learners were further able to control and regulate the amount of substances, such as HCl and magnesium ribbons. The latter also applied SL in their study by checking the effect of virtual laboratories on learners' high-order thinking skills when learning about chemical equilibrium.

Chemistry Virtual Laboratory (CVL)

The CVL was used by two studies, namely, Gambari et al. (2018) and Manyilizu (2023a). Soraya et al. (2023) found CVL to be adequate and efficient in that it enhances learners' self-efficacy, research techniques and abilities, problem-solving abilities, scientific knowledge, technical knowledge and a mental grasp of chemistry. Moreover, it does away with the requirement that instructors and students be present in person during practical sessions (Manyilizu 2023a). Gambari et al. (2018) used CVL to enhance collaborative learning through the use of a computer. Collaborative learning yields positive outcomes for the learning process as it supports active learning. Gambari et al. (2018: p. 251) used CVL in four stages of "chemistry lecture note" where learners accessed the experiment's procedure, a video of chemistry experiment which allowed learners to understand how the experiment should be done, the virtual chemistry lab where learners were able to perform the experiment, and a quiz which was based on the experiment that was performed. Manyilizu (2023a) used CVL for topics such as Mole Concept and Related Calculation, Volumetric Analysis, and Laboratory Techniques and Safety, which are reported to be performing poorly.

VICH-Lab

Fitriyana et al. (2024) used VICH-Lab in blended online learning of chemical equilibrium topics in their study. This was motivated by the fact that the software, which is provided in the form of Moodle, contains a simulation experiment covering sub-topics of chemical equilibrium (Fitriyana et al. 2024). Furthermore, owing to its availability online, learners can access it at their convenience or even redo the experiments. However, because this software supports blended learning, learners chose to use it to engage in online discussion forums after the experiment. This is beneficial for the learning process, as learner engagement creates social interactions.

Scientific Investigation Lab (SIVRLAB)

An inquiry-based, immersive VR software, SIVRLAB, was developed by Lai et al. (2022) to facilitate topics such as oxidation-reduction and cells for high school learners. Learners were able to conduct tests on six metal powders, determine the ideal pairings for oxidation-reduction processes, record test outcomes, and use the outcomes to assemble a chemical cell. This shows how immersive VR can be used to support process-driven science skills that are frequently challenging to duplicate in conventional screen-based laboratories.

Java Enabled Software

Cai et al. (2014) used a java enabled AR based software on the topic of the composition of a substance. Learners were expected to use markers to create molecules and substances and depict particles as though they were conducting an actual laboratory experiment. The software required learners to be self-directed and independent of the teacher's instructions. Furthermore, the software uses a 3D format, which is more influential and user-friendly than 2D formats (Cai et al. 2014). The fact that only one study AR-based software presents a distinct contrast in the technological approach. Moreover, this provides a picture of a promising but underexplored branch of VL research, suggesting a potential avenue for enhancing spatial reasoning and hands-on, constructivist learning without full VR immersion.

Physics Education Technology (PhET) Interaction Simulation

According to Fuada et al. (2023), PhET is one of the most potent and amazing simulator inventions and is extensively employed in STEM-based education. Furthermore, it is crucial to clarify abstract concepts (Juwairiah et al. 2022). Likewise, rather than focusing solely on conceptual learning, Yakob et al. (2023) used PhET in a chemistry topic of acid-base to develop a "classroom based authentic assessment instrument" (p. 631). The purpose of this study was to observe the enhancement of learners' performance in science. This represented a shift from using VLs purely for instruction or practice to employing them for embedded performance-based evaluation. The aim was to monitor advancements in scientific performance through assignments that replicate actual scientific investigations using a simulation environment.

DISCUSSION

Science Process Skills

Science process skills are one of the most important skills be it in life or for science purposes, as they shape how learners behave outside the classroom (Suman 2017). From this review, two studies specified the science process skills in the text. Hung and Tsai (2020) focused on skills such as coming up with a target question, identification and choosing variables, choosing data, categorising and aligning data accordingly, interpreting, and applying data. Yakob et al. (2023) went a step ahead by measuring the skills of problem formulation, prediction formulation, variable formulation, operational definition formulation, experiment data communication, experimental data analysis, and conclusion formulation. It would be expected that reviewed studies would accommodate a myriad of science process skills steps since VLs are reported to enhance learners' science process skills (Yusuf et al. 2025). However, this was not the case.

Teaching Approach

Teaching strategies are important because they can lead to progressive learning outcomes if chosen well. In this review, approaches such as problem solving, inquiry-based learning, expository teaching style, metacognitive scaffolding strategy, and collaborative learning were identified. The inquiry-based learning approach was employed in three studies, problem solving in two, and the other approaches in one study each (see Table 2 and Fig. 3). Meanwhile, a bigger chunk (eight studies) did not specify the teaching approach employed in their title, abstract, or text (see Fig. 3). All the identified strategies belong to the sea of learner-centred strategies that most curriculums, such as the South African (SA) Curriculum and Policy Statement (CAPS) encourage (DBE 2011). For example, Dzaiy and Abdullah (2024) identify problem-based learning amongst others, as an active learning strategy that learners interrogate authentic issues, with teachers facilitating the process (Dzaiy and Abdullah 2024). Furthermore, active learning strategies yield learners' interaction motivation and higher-order thinking skills (Dzaiy and Abdullah 2024), as per CAPS expectations (DBE 2011).

Problem Solving

In the current review, one study (Scherer and Tiemann 2014) used problem solving as a strategy. Problem solving has many advantages, such as enhancing learners' lesson objectives and practical experimental abilities, which are important for their cooperation and industry in the future (Su 2024). Learners who are exposed to the skill develop strong thinking capacity and laboratory skills, such as problem analysis, hypothesis generation, experimentation, and drawing conclusions (Egbodo and Uzoamaka 2025). More so, studies demonstrate how VLs improves learners' problem-solving skills (Chattopadhyay 2025; Egbodo and Uzoamaka 2025; Lampropoulos et al. 2025). The reviewed study by Scherer and Tiemann (2014) analysed the components of learners' problem-solving skills in a virtual science environment. The study found that the psychological aspects of problem solving and interactivity can be transformed into more complicated aspects of problem solving in science learning areas.

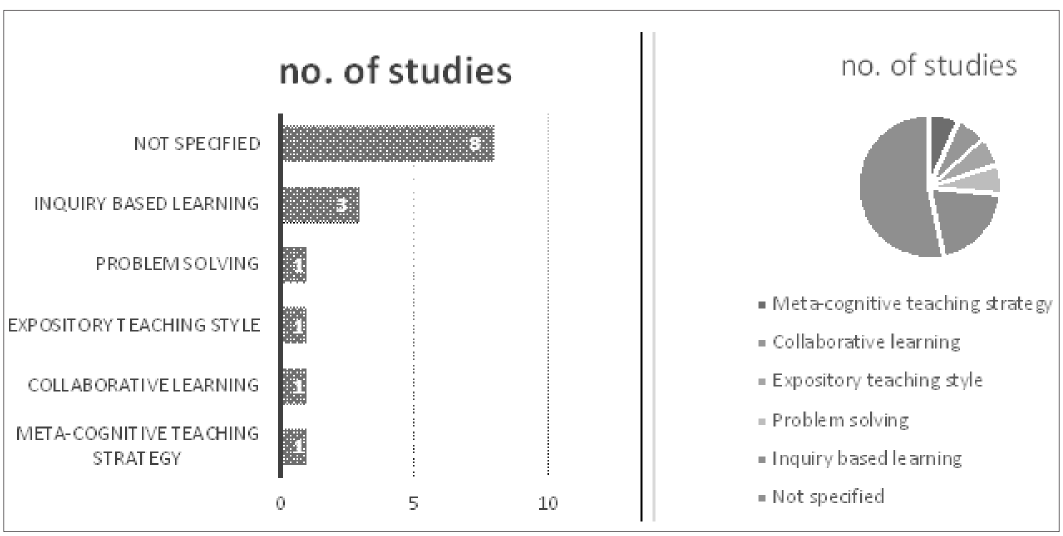

Fig. 3. Bar and pie graphs demonstrating teaching approaches used in VLs

Inquiry-based Learning

Another learner-centred approach, inquiry-based learning, aligns well with teaching and learning through VLS. According to Mafarja et al. (2025), VLs allow teachers to develop and apply inquiry- based instructional approaches. In this review, inquiry-based learning appears in three studies, namely, Cai et al. (2014), Hale-Hanes (2015), and Lai et al. (2022). Cai et al. (2014) focused on designing inquiry-based AR Reality resources for learning. In the process, learners were exposed to 3D models of microparticles that they could assemble, blend and engage with through markers, carrying out a number of inquiry-based experiments in the process. It is clear that the approach improves learners' learning interest, as Bogador et al. (2024) alluded to. Hale-Hanes (2015) used an open-ended inquiry approach in their study, where learners were provided with tools and animations to help them create visual representations of their conceptual model to illustrate acid-base chemistry through ions. Learners were motivated and were able to expand their understanding of ions and atoms to a more innovative level, where they could build on their models. Lai et al. (2022) designed inquiry-based, immersive VR, Scientific Investigation Lab (SIVRLAB) that enabled situational learning tasks. Learners relied on the virtual tutor as a guide in their inquiries. Learners were able to observe and control things like salt bridges and test tubes, consistent with Natale et al. (2021), who alluded to the fact that inquiry-based learning activities in virtual platforms provide an arena for learners to undertake essential epistemic approaches that yield scientific literacy. The instructional design comprised six strategies to make inquiry learning effective (Lai et al. 2022).

Expository Teaching Style

Only one study, Winkelmann et al. (2014), used the expository teaching style. This teaching style underlines the importance of imparting knowledge to learners through lectures, demonstrations, and study reports using sources such as textbooks, references, and personal experiences (Nasution 2020). In the context of Winkelmann et al. (2014), learners were involved in decision-making regarding settings for the experiment and their use of laboratory resources, which seemed to stimulate curiosity among learners regarding the experiment, who felt a bit independent in following the procedure. This finding suggests that even within seemingly directed contexts, a VL's instructional usefulness may depend more on the level of meaningful engagement it facilitates than on its nominal teaching approach. Future VL designs might therefore benefit from purposely incorporating strategic choice points inside guided learning sequences to capture this motivational and cognitive benefit.

Metacognitive Scaffolding Strategy

Metacognition is an important aspect of education as it focuses on knowing what one knows, what one does not know, and how to control and regulate this kind of thinking (Mahdavi 2014). According to Alias (2012), cognitive and metacognitive scaffolding strategies offer guidance, support, recommendations, and prompts on the materials, tools, and techniques related to learning management and problem solving. In this review, Hung and Tsai (2020) used the metacognitive scaffolding strategy in their study, which, together with the virtual laboratory, had a positive effect on learners' data modelling abilities. Notably, despite the acknowledged significance of these strategies, this was the only study in the review that specifically combined metacognitive scaffolding with a VL, indicating a sizable gap in the literature. To go beyond conceptual modelling and actively enhance students' higher-order thinking and self-regulated learning skills, future VL design and implementation should place a strong prioritisation incorporating organised metacognitive aids.

Collaborative Learning

This is one of the most popular and successful teaching strategies (Barragán et al. 2024). Gambari et al. (2018) used this strategy in their study to explore the effect of virtual laboratories on secondary school chemistry learners' achievements. In this context, learners had to co-teach each other in their groups of three, where they also assigned each other different roles, which they exchanged as those who were teaching would become the audience and so on. This positive observation is commendable as VLs are noted as enablers of collaborative learning (Lampropoulos et al. 2025), which is learner-centred and encouraged by curricula such as CAPS (DBE 2011).

Topics

Chemistry topics such as states of matter, chemical reactions, illustration of gaseous particles, compounds, separation of substances from a mixture, physical and chemical changes of matter, introduction to qualitative analysis, identification of cations and anions, specific heat, chemical equilibrium, acid-base, substance purification, stoichiometry, and thermochemistry were part of the studies under review (see Table 2 and Fig 4). A topic such as chemical reactions appeared in two studies, namely, Winkelmann et al. (2014) and Yakob et al. (2023), whereas the other topics appeared once in each study. Likewise, while studies such as Herga et al. (2016), Gambari et al. (2018), and Yakob et al. (2023) included six, two, and five topics respectively, while the other four studies, such as Scherer and Tiemann (2014), Winkelmann et al. (2014), Hung and Tsai (2020), and Amin and Ikhsan (2021) had one topic each appearing in their studies. Moreover, it was not clear from the remaining eight studies which topics they covered.

However, research has reported that some chemistry topics are difficult. For example, Kyado et al. (2021) found that thermodynamics, ionisation, chemical kinetics, redox reaction, isomerism, quantum number, stoichiometry, hydrophobic, enthalpy, mole concept, atomicity, enantiomers, nuclear chemistry, and quantitative analysis were difficult topics. Musonda (2021) identified topics such as the mole concept and stoichiometry, electrolysis, organic chemistry, and redox reactions as difficult for learners. Other researchers, such as Tilahun and Tirfu (2016), identified chemical bonding, thermodynamics, chemical equilibrium, kinetics, and colligative properties as difficult topics. One of the reasons identified as a contributor was the lack of and insufficient apparatus and resources (Musonda 2021; Tilahun and Tirfu 2016). VLs are known to close this gap, and it is interesting that some of these topics were covered in this review. For example, Yakob et al. (2023) and Amin and Ikhsan (2021) covered stoichiometry and chemical equilibrium topics, respectively. Nonetheless, it is alarming that topics such as electrolysis, or-

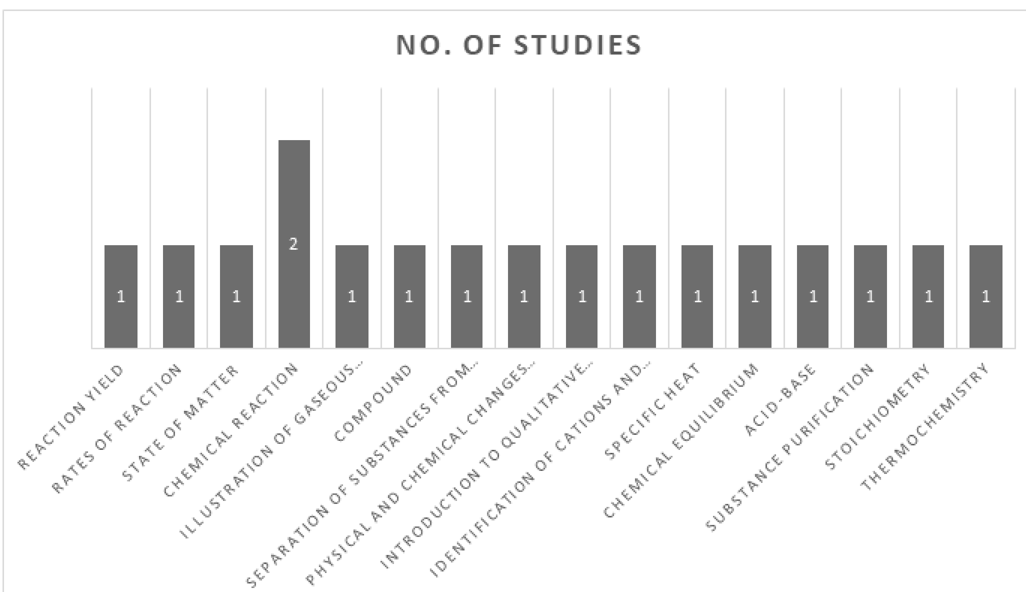

Fig. 4. Graph demonstrating a chemistry topics' frequency of appearance in the reviewed studies

ganic chemistry, enthalpy, isomerisation, and redox, which were identified above, were not covered.

Effect of VLs on CBE Learning

After reading the text of the studies under review, the following themes emerged, namely, achievement, motivation, self-efficacy, acquisition of knowledge, enhanced practical skills, self-directed learning, higher-order thinking skills, social and teaching presence, and social interactions.

Achievement

Several studies have reported the effect of VLs on achievement. For example, Gambari et al. (2018) explored the effect of VLs on achievement in the context of gender. After receiving VL lessons, female learners in homogeneous groups outperformed those in heterogeneous groups. The same was noted by Hale-Hanes (2015), Wolski and Jagodziñski (2019), Herga et al. (2016), and Fitriyana et al. (2024), who noted a positive effect of VLs on learners' achievement in Chemistry. Cai et al. (2014) went further to note that VLs have a more positive effect on low achievers than on high achievers. Achievement in education is one of the main aims that teachers, practitioners, parents, and role players always carry in their minds whenever they look for solutions, and it is therefore satisfying to note the positive impact VLs play in reaching that goal.

Motivation and Self-efficacy

Self-efficacy refers to the belief that one can learn or perform tasks at specific levels (Schunk and DiBenedetto 2020). Learners should be confident when using VLs in their learning chemistry. This is not far from motivation, which is at the centre of determining the success of the learning process (Filgona et al. 2020). Consequently, highly motivated students are more likely to pick things up quickly and make any lesson enjoyable to teach (Filgona et al. 2020). Wolski and Jagodziñski (2019) report how both learners' self-efficacy and self-confidence were enhanced in order to work in the actual laboratory after being exposed to VLs, with the former consistent with the observation by Kolil et al. (2020). Cai et al. (2014) also noted that learners developed a positive attitude towards the AR simulation software, while Hale-Hanes (2015) noted how the use of VLs reduced learners' emotional filter towards chemistry, consequently improving their confidence about learning the chemistry content.

Self-directed Learning (SDL)

SDL refers to the mindset that results from a person's desire to study independently (Hidayah et al. 2024). It is connected to self-regulation and self-efficacy (Hwang and Oh 2021). Fitriyana et al. (2024) highlighted how the use of VL allowed learners to be self-directed when learning about chemical equilibrium. This finding is consistent with the contribution of Sapriati et al. (2023), who suggested that, in the long term, self-regulated learning, a precursor to SDL, develops in learners who are exposed to virtual environments. As a result, learners at any age may be able to undertake tasks with or without the teacher's guidance.

Acquisition of Knowledge

Constructivist in nature (Chand 2023), knowledge acquisition is an important aspect of education as it can lead to knowledge creation, application, and storage (Matar and Raudeliûnienë 2021). This is also in line with the specific aims of the SA Physical Science curriculum (DBE 2011). According to Herga et al. (2016), chemistry knowledge is best acquired in the laboratory. Consequently, knowledge application plays a very important role in the laboratory, which in this case is virtual. Three studies, Herga et al. (2014), Herga et al. (2016), and Wolski and Jagodziñski (2019), found VLs to be a better platform for knowledge acquisition, a finding that was amplified by Lampropoulos et al. (2025), who also added knowledge retention and comprehension to the equation. Moreover, Wolski and Jagodziñski (2019) further indicated that learners' capacity to apply knowledge was enhanced, such that they could solve problems in scenarios they were familiar with from previous classes. In a world that requires solutions in a number of sectors, it is important that learners are exposed to VLs during the learning process.

Higher Order Thinking Skills

Linked to knowledge acquisition, teaching with the aim of achieving higher-order thinking skills in learners is important. This can be noted from one of the aims of the SA Physical Sciences curriculum, CAPS, whose principles include, among others, high knowledge and high skills (DBE 2011: 4). Further, the curriculum aims to produce learners that are capable to "identify and solve problems and make decisions using critical and creative thinking" (p.4). Only one study in this review, Amin and Ikhsan (2021), explored the effect of VLs on learners' higher-order thinking skills, which they found to be positive. Jakob et al. (2023) also noted how the use of "authentic assessment instruments" in a VL improved learners' critical thinking skill.

Enhanced Laboratory Skills

The application of knowledge in the laboratory, as indicated above, requires learners to have laboratory skills. Laboratory skills are important in the science fraternity, as industries and corporate worlds are reliant on them. Manyilizu (2023b) noted an enhancement of practical skills in real laboratories after female learners initially encountered virtual laboratories. Hung and Tsai (2020) discovered how VLs improve learners' data modeling skills. Jakob et al. (2023) noted that improvement from the virtual perspective. These notable improvements are consistent with the observations of Alhashem and Alfailakawi (2023).

Community of Inquiry and Social Interactions

Garrison's (2009) community of inquiry framework introduces three aspects that are fundamental to interactions in an online environment. These aspects are social, cognitive, and teaching presence. Winkelmann et al. (2014) noted how SL application provides an arena for social presence, but that was done under the introduction, and not under findings or conclusions. However, the VICH-Lab used by Fitriyana et al. (2024) enabled social interactions between learners because of the software's blended learning nature, and learners were able to discuss and interact after the experiment. Nonetheless, this review identifies a gap in the effect of VL through the lens of the community of inquiry framework.

CONCLUSION

This review provides a picture of the use of VLs in CBE. The studies were conducted in Slovenia, China, Nigeria, Taiwan (twice), and Tanzania (twice). Consequently, three continents, Africa, Asia, and Europe, contributed to the body of knowledge regarding the use of VLs in CBE, while the same cannot be said about other continents such as North and South America, Oceania, and Antarctica. However, given that the countries of publications could not be traced from nine studies, there is a possibility that those studies took place in any of those continents. Therefore, it is recommended that authors specify the countries where the studies took place in the text, specifically in the 'sampling and population' section. It was also alarming to note that only 15 studies on VLs in CBE were conducted, at a rate of three studies every two years, which is not sufficient. One would expect more studies from 2020, given the challenges brought about by the pandemic. The software use was also not consistent across the 15 studies, with Virtual Chemical Laboratory Crocodile Clips Chemistry, SL, and CVL being applied in two studies each, while other software were applied in one study each. Nevertheless, the mentioned software had a positive effect on the learning process. Unfortunately, three studies did not specify the type of software used in their study. This was a missed opportunity, as it would have helped the reader understand how the chosen software assisted in the simulation of chemistry learning. Moreover, more research has been conducted at the high school level (13 studies) than at the primary school level (two studies). It is recommended that future research be conducted at the primary school level, as these institutions are where science is first introduced to learners. Studies should also emphasise the process skills covered, as only two of the 15 studies under review did so. Laboratories are arenas for hands-on activities, and in this case, a huge gap can be noticed. This review also identified problem solving, inquiry-based learning, expository teaching style, metacognitive scaffolding strategy, and collaborative learning in the studies under review. However, considering the long list of effective teaching strategies, one would expect more teaching approaches in addition to the ones extracted. Nonetheless, they may have been used in the other eight studies that did not specify the teaching approach.

RECOMMENDATIONS

It is recommended that future studies specify these important details. The literature has also identified studies that are perceived to be difficult for learners. Nonetheless, this review identified only stoichiometry and chemical equilibrium, which participants tried to address with VLs. Other topics such as thermodynamics, ionisation, chemical kinetics, redox reaction, isomerism, quantum number, hydrophobicity, enthalpy, mole concept, atomicity, enantiomers, nuclear chemistry, quantitative analysis, electrolysis, organic chemistry, chemical bonding, thermodynamics, chemical equilibrium, and colligative properties were not included in the reviewed studies. Future research should focus on the use of VLs for these topics. This review also discovered the positive effect of VLs on achievement, motivation, self-efficacy, knowledge acquisition, practical skills, self-directed learning, higher-order thinking skills, and social interaction. However, none of the studies indicated any effect of VLs on social, teaching, and cognitive presences in the community of inquiry framework. Future research should focus on this area.

LIMITATIONS

This review focused only on primary and secondary school chemistry and excluded work covering tertiary institutions, such as universities and colleges. The databases used during the search were Scopus, Eric-EBSCO, and ScienceDirect, and focused on papers from 2014 to 2024 and included no work before 2014. This review did not include work from Google Scholar or any other database, which may have provided more information than was acquired. In addition, the review was conducted in May and June 2024, and hence, it did not include studies from July 2024 to the date of submission of the manuscript. Sources reviewed were only empirical research articles, while excluding review papers, books and conference papers. Moreover, non-English papers were not included. Hence, the outcomes of this review cannot be generalised to a broader perspective.

CONFLICT OF INTEREST

There are no conflicts of interest to declare in this study.

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