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Virtual laboratory applications in chemical education: Literature review of the methodology, learning theories and outcomes, and pedagogical elements

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Abstract

This study presents a literature review of empirical research conducted between 2012 and 2022 on the use of virtual laboratories and other digital learning technologies in chemistry education. A crucial component of chemistry education is practical laboratory courses. They can, however, be expensive and time-consuming. Students need access to well-equipped labs, which may be difficult due to the expense of the necessary equipment or a pandemic lockdown. What research has been done on virtual laboratories, and what instructional and technological features are crucial? After reviewing 85 articles published in peer-reviewed scientific journals, the study's findings indicate that virtual laboratories can be more effective instructional tools than passive teaching strategies but can also be as effective as hands-on laboratories. Additionally, this review identified the pedagogical design components used in virtual laboratories. While immersive VR and NUIs have gained popularity, most studies used 3D desktop technology. Combining virtual and conventional methods yields better results.

Keywords: Virtual laboratories, virtual reality, immersive virtual reality, chemistry NUIs, 2D chemistry technology, 3D chemistry technology, chemical education

Introduction

Chemistry can be studied quite effectively using experiment-based learning. As a result, the chemistry laboratory is crucial to the learning process because it serves as a setting for students to acquire knowledge through theory, research, and scientific advancement. According to the constructivist approach, students' active participation in the learning process is crucial (Bernard *et al*., 2004). In a constructivist learning environment, students actively develop their knowledge by reasoning, doing, and interacting with their surroundings. (Tatli, 2011) [39]. Because of this, the laboratory is crucial to the teaching and learning of chemistry (Leite *et al*., 2002) [22]. Science educators have argued that using laboratory activities can have a significant positive impact on students' learning (Taşdelen, 2004) [35]. In chemistry coursework, the laboratory component has been given a prominent and central position.

In a way, individual differences would be eliminated in lab studies. As a result, all tools and techniques used in laboratory research are also components of individual training (Tatli *et al*., 2010) [38]. Additionally, using a lab to teach students develops their capacity for reasoning, critical thinking, a scientific viewpoint, and problem-solving (Odubunni *et al*., 1991) [28]. Students are encouraged to think, study, and conduct experiments like scientists with the help of these abilities (Bozdogan *et al*., 2004) [6]. The aim of chemical education today is to develop young people with strong problem-solving skills who analyze the methods used to discover scientific knowledge and applications. Teaching, which is quickly eschewing conventional methods, must identify the causes of earlier issues and adopt new strategies to meet the demands of the contemporary information society (Rusten, 2004) [32].

However, conducting chemistry experiments in a real lab has some drawbacks because it requires more time and involves students using risky and expensive chemicals and equipment. Utilizing a virtual laboratory overcomes common issues associated with a real laboratory. The virtual-based experiment is a relatively affordable, safe, effective, and efficient alternative form of media. When conducting an experiment in a virtual setting, students actively participate. They can conduct the experiment alone or with a team of peers (Dede *et al*., 1994). Additionally, due to the adaptability of virtual environments, abstract chemistry concepts that are ineluctable become more concrete, real-world examples can be used to illustrate lessons, and students can progress at their own pace and according to their individual needs (Sanger, 2000 [33]; Pekdag, 2010) [29].

The use of a virtual laboratory can enhance learning opportunities, inspire students to conduct experiments in groups, and help them hone their experimental techniques. To increase learning activities and foster the development of problem-solving skills, virtual laboratories can thus be defined as a collection of software programs that can visualize abstract or complex phenomena observed in real laboratories (Tatli *et al*., 2012) [37]. If the actual experiments are hazardous, using virtual laboratories allows students to conduct them safely from anywhere at any time. Because real laboratory experiments require more expensive equipment and supplies, using this lab is also less expensive (Totiana *et al*., 2012 [40]; Hidayat *et al*., 2015) [16]. Previous studies have demonstrated that using virtual laboratories is more effective than traditional teaching (Arista *et al*., 2018) [5] and that learning in laboratories increases learners' independence and conceptual understanding. Additionally, conceptual learning (Tsovaltzi *et al*., 2010) [42] and learning innovations (Ifthinan *et al*., 2019) [17] can be accomplished using virtual laboratories.

Due to the COVID-19 pandemic, many chemistry courses are now required to be taken online, which has changed how chemistry is taught all over the world. Adjustments have been made to the educational system as a result of the

COVID-19 pandemic. It has gotten harder for both students and teachers to adjust to digital technologies and the new mode of learning as e-learning has spread across the globe. The most advantageous part of the chemistry curriculum was the practical, or wet lab, section. This abrupt and significant change forced chemistry educators to reconsider their pedagogy in order to conform to the new paradigm, but it also provided a chance to look at technological pedagogical content knowledge and its application in uncertain times.

Virtual labs are learning environments that are computer-simulated and can range from straightforward 2D visualizations of laboratory experiments to sophisticated 3D simulations that attempt to mimic real laboratory environments (Jones, 2018). It is even possible to perform realistic laboratory handling while fully immersed in the virtual laboratory environment thanks to recent advancements in virtual reality (VR) technology (Han *et al*., 2017 [14]; Kim *et al*., 2019) [19]. In comparison to conventional hands-on laboratories, virtual laboratories can provide several advantages, including lower costs, greater accessibility, time savings, safe environments, and the flexibility of self-regulated learning (Ali *et al*., 2020 [3]; Falcouner *et al*., 2018). However, depending on how the virtual lab is used, the lack of actual instructors and a true laboratory atmosphere may prove disadvantageous (Lynch *et al*., 2017) [23].

Virtual laboratories will likely expand in variety in the near future as distance learning gains popularity. However, creating such a sophisticated virtual learning environment is not always simple. To design an effective learning experience, a multidisciplinary team with varying levels of expertise is frequently needed (Mikropoulos *et al*., 2011) [26]. Furthermore, studies have shown that there are other elements that contribute to the design of successful virtual learning environments in addition to technology. If the technological design is not done properly, it may, in some cases, even inhibit cognitive learning processes (Mayer, 2014; Makransky *et al*., 2019) [24]. To maximize the value of the virtual laboratory experience, a rigorous instructional design that makes use of tried-and-true learning theories and instructional support is needed.

Research questions

Through the literature review, the study examined three research questions. They are as follows.

1. What were the key objectives, research design, overall outcome, and learning outcomes of studies investigating the use of virtual laboratories in chemical education?
2. What technologies were applied to create virtual chemical laboratories?
3. What pedagogical elements and learning theories have been used in virtual chemical laboratories?

Methodology

Database, keywords, inclusion & exclusion criteria, coding

We adhered to the PRISMA tenets and guidelines to conduct the literature review (Moher *et al*., 2009) [27]. These recommendations assist researchers in conducting accurate and thorough systematic literature reviews. The author must outline the search strategy, eligibility requirements, selection procedure, and data collection process. Searches for articles were conducted using three scientific databases: Web of Science (WOS), Scopus, and ERIC. Search terms include "virtual chemical/chemistry lab," "game-based chemical/chemistry lab," "two- or three-dimensional chemical/chemistry lab," and "virtual simulations and animations in chemical/chemistry lab." Table 1 provides a list of the inclusion and exclusion criteria used to weed out irrelevant articles. Figure 1 summarizes the findings. A total of 85 publications were included in the literature review after the downloaded articles were screened using the inclusion and exclusion criteria.

Table 1: Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
Peer reviewed journals and conference proceedings	Reviews, thesaurus, dissertations, editorials, commentaries, abstracts, non-peer reviewed publications
Articles must be written in English	Articles not written in English
Must contain 2D, 3D, simulations, animations, or virtual reality application	Augmented reality
Virtual laboratories for chemical education	Publications that are not accessible
Must contain laboratory practices	Virtual applications used to teach chemical concepts that are not laboratory oriented.

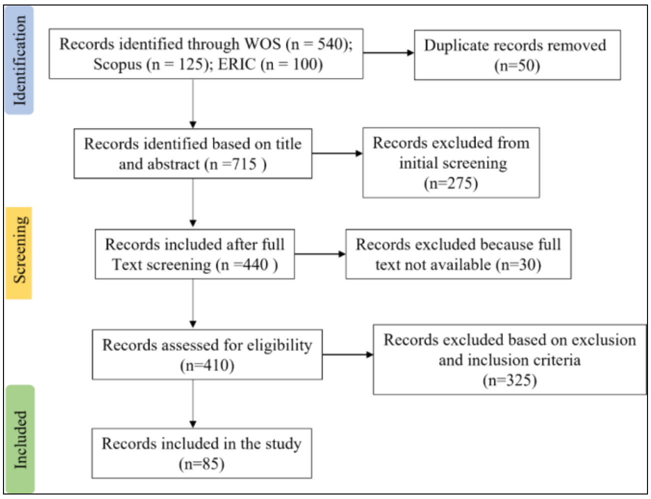

Fig 1: PRISMA flow chart

Results

Nature of the study

The three main research purposes of the publications that discuss the use of virtual chemical laboratories are comparative, evaluative, and technical studies. Comparative studies examine two or more intervention groups and contrast the media or virtual laboratory layout. According to Mayer *et al*. (2005) [25], the former is known as media comparison and the latter as value-added research. In a study on media comparison, the learning outcomes of an experimental group using a virtual laboratory application for chemical synthesis are contrasted with those of a control group using the same learning content but a different instructional medium. In value-added studies, a virtual laboratory application's basic version is tested with a control group, while the treatment group makes one design change or addition to the basic version while using it. Evaluation studies only take the virtual laboratory group into account when assessing a specific result. To assess the user experience and usability of the system, one can measure affective responses such as attitude, satisfaction, or self-efficacy of the system, one can measure affective responses such as attitude, satisfaction, or self-efficacy. We have categorized these publications in this case as "user studies." Without a control group, other studies have looked at how well the virtual laboratory performs to assess the performance gain or assessment methodology. The term "performance assessment" refers to this category. Technological studies describe the design and development of the virtual laboratory rather than performing any measurements to evaluate it. Although these studies don't provide any quantifiable results, they are still helpful for this review because they outline the technological advancements made in virtual chemical laboratories.

We found that many of the empirical studies (n = 43, 51.2%) could be classified as "comparative studies." Many studies in this category compared media (n = 35) versus value-added studies (n = 8). "Evaluate study" is the second most popular research objective (n = 33, 39.3%). Many studies in this category compared user studies (n = 21) with performance assessments (n = 11). The fewest number of studies (n = 8; 9.5%) were found to fall into the category of "technology studies." These studies aim to describe the creation of such applications as well as the design and technology of virtual chemical laboratories.

Data evaluation and Learning outcomes

Evaluation methods consisted of quantitative and qualitative techniques, lab exercises, real-time evaluation, course grades, questionnaires, interviews, and observations. Real-time evaluation refers to gathering information within the virtual lab application that can be retrieved using log files. Learning outcomes that were assessed in the reviewed studies are divided into three domains: cognitive, affective, and skill based (Kraiger *et al*., 1993) [21]. The term "cognitive domain" refers to a participant's cognition, which includes declarative knowledge (knowledge of facts and concepts), procedural knowledge (knowledge of how to carry out a task), and conditional knowledge (knowledge of when to apply principles to solve problems) (Anderson *et al*., 2021) [4]. The term "affective domain" describes a participant's subjective response, which includes attitude, usability, and self-efficacy. Technical or practical skills of the participant, such as practical laboratory skills, are referred to as skill-based domains.

Measurements of cognitive, affective, and skill-based learning outcomes have been made to determine the efficacy of virtual chemical laboratories using a combination of quantitative and qualitative evaluation methods. Figure 2 contains a bar graph illustrating the proportion of evaluation techniques applied in comparison and evaluation studies. Between comparative and evaluative studies, there is a clear distinction in how these methods are applied. For comparative studies, tests are the most frequently used evaluation method (n = 15, 31%), whereas interviews are the most frequently used evaluation method (n = 11, 12.9%) for evaluative studies. Comparative studies also appear to have used qualitative evaluation techniques, such as questionnaires (n = 30, 35.3%) and observations (n = 10, 11.8%), to assess the affective outcomes of participants. Additionally, we note that real-time assessments were used more frequently in evaluative studies (n = 5; 5.9%) than in comparative studies (n = 3; 3.5%), while laboratory experiment grades were frequently seen in comparative studies (n = 9; 10.6%).

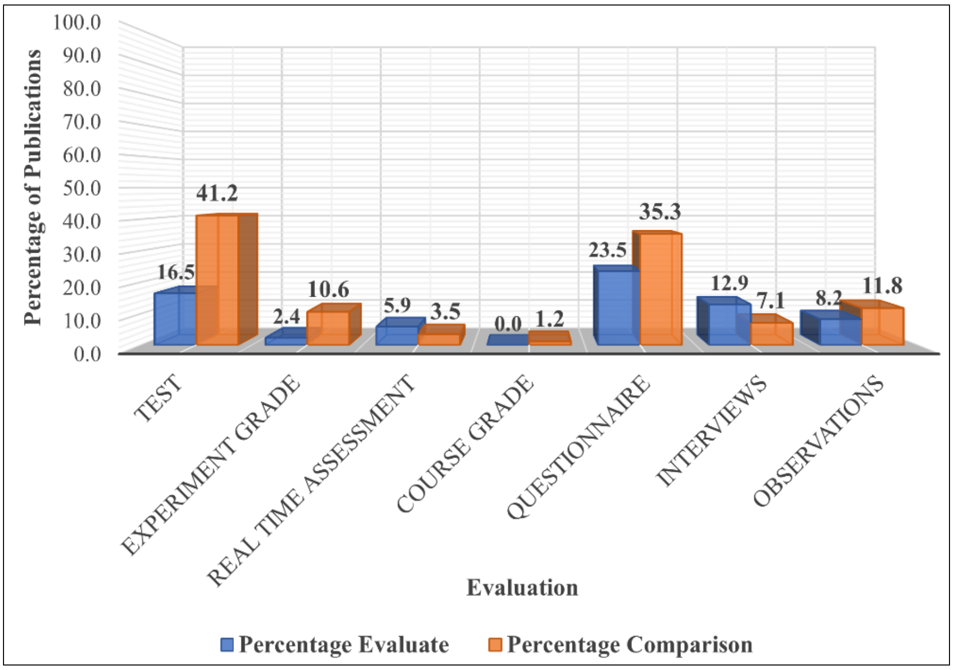

Fig 2: Bar graph showing the percentage of the evaluation methods used in evaluate (blue) vs comparison (orange).

The percentage of evaluation methods used in comparative and evaluation studies is depicted in a bar graph in Figure 3. When examining learning outcomes, we discovered that a greater percentage of comparative studies measured cognitive (n = 40, 47.1%) and affective learning outcomes (n = 26, 30.6%), as shown in Figure 3. However, evaluation studies frequently assessed participants' cognitive (n = 17, 20%) and affective (n = 13, 15.3%) outcomes. This is because these studies evaluate participant perceptions and the usability of the virtual laboratory. The skill-based outcome has been the least thoroughly examined in both comparative (n = 8, 9.4%) and evaluative (n = 1, 1.2%) studies. When we investigated the sub-categories of these learning outcomes in Figure 4, we discovered that declarative knowledge (n = 38, 44.7%) and usability (n = 23, 27.1%) are the most measured learning outcomes in the cognitive and affective domains, respectively.

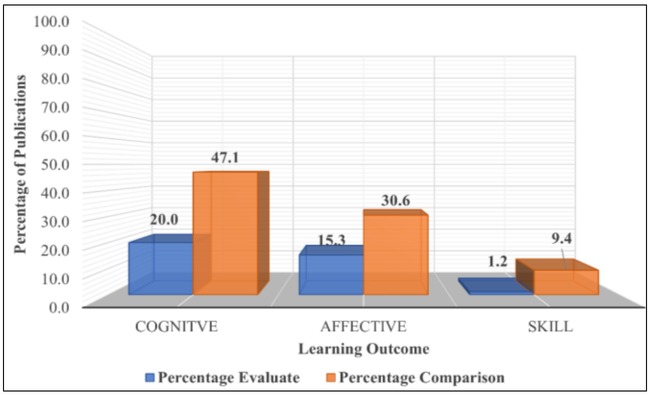

Fig 3: Bar graph showing the percentage of the learning outcomes measured in evaluate (blue) vs comparison (orange).

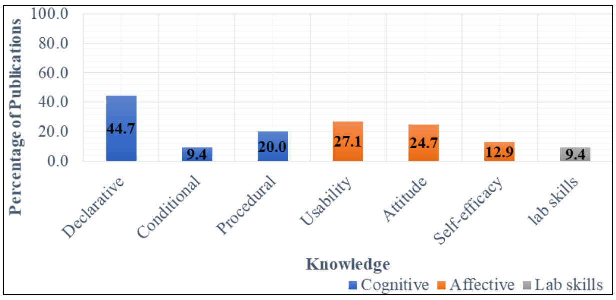

Fig 4: Bar graph showing the percentage of the learning outcome sub-categories measured in the cognitive (blue), affective (orange) and skills (grey) domain respectively.

Technology

Display technologies, which can be categorized as 2D desktop, 3D desktop, or immersive VR, are graphic features used with a specific display device. Virtual chemical laboratories that are displayed on a desktop monitor and have a 2D representation of the environment and objects are described in studies under the 2D desktop category. Virtual chemical laboratories that are 3D in nature—i.e., have depth to them and are made of 3D geometries—are also displayed on desktop monitor displays in the category of 3D desktop software. The use of contemporary VR devices that completely immerse the user in the virtual environment without allowing for visual interaction with anything outside of the display is covered in studies under the category of immersive VR. These VR devices can also display a different image for each eye, enabling a 3D stereoscopic view that gives the impression of real depth. The use of unique input devices (NUIs) in addition to display technology can be differentiated further. Input from human motion or gestures is used by NUIs to operate the system "in such a way that the user is not aware of an interface" (Jagodziski *et al*., 2015). These include gadgets with sophisticated tracking features like movement or rotational tracking, spatial tracking, and hand- or body-gesture tracking.

Figure 5 displays the trends in virtual technology between 2011-2022. Research utilizing 2D and 3D desktop technologies to create virtual chemical laboratories has continued to be a significant area. Since 2017, there has been an increase in the use of immersive technology. Chemical experiments or laboratory settings are visually displayed using display technologies. Most publications (n = 29, 34.1%) reported using virtual laboratories that used 2D desktop technology. 3D desktop technology came in second (n = 27, 31.8%), and immersive VR came in third (n = 16, 18.8%).

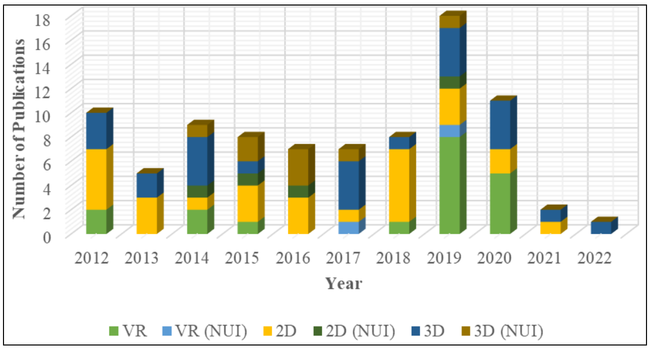

Fig 5: Trends in virtual technology (2012-2022)

Pedagogical elements

Identification of the learning theory and instructional support components used in these publications allows for an analysis of the instructional design of the virtual chemical laboratories. This was accomplished by looking at the learning theories that have been used in conjunction with the terms taken from the collection of Kebritchi *et al*., (2008) [18]. Similarly, to identify the terms for looking at instructional support elements, Wouters *et al*., (2013) [45] list was used. According to our research, constructivism (n = 3) and inquiry-based learning (n = 7) are two of the most popular learning theories for virtual chemical laboratories. However, a significant portion of the publications (n = 63, 74%) did not mention any specific learning theory. Figure 6 graphically displays the number of learning theories reported in the reviewed articles. According to our observations, the top 3 most frequently used instructional support elements in virtual chemical laboratories are feedback (n = 11), scaffolding or guidance (n = 8), and modality (n = 6). Nevertheless, much like learning theories, many publications (n = 55, 72%) do not mention any kind of instructional support.

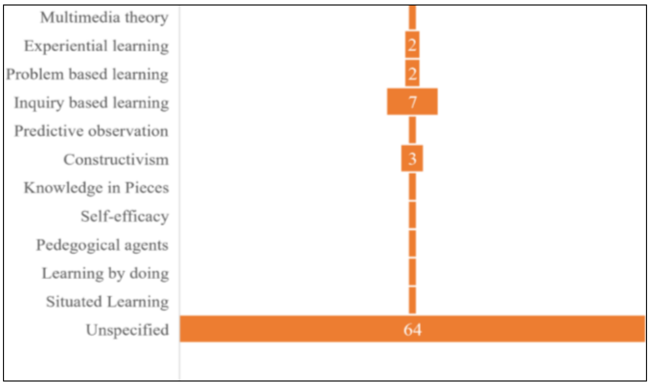

Fig 6: Learning theories reported in reviewed articles.

Discussion

Findings of the study imply that a vast majority of studies have conducted media comparative studies to compare the efficacy of virtual labs and conventional teaching techniques. Comparative analysis primarily uses quantitative evaluation techniques, such as knowledge tests to look at cognitive learning outcomes and lab practical assessments to look at practical laboratory skills. Declarative knowledge has received the most attention in this study, which is consistent with prior assessments of virtual laboratories (Brinson, 2015). Comparative studies also included qualitative evaluation techniques like questionnaires, interviews, and observations. According to the findings of studies comparing different media, the efficiency of virtual chemical laboratories varies greatly depending on the traditional teaching technique that is used as a reference.

Virtual laboratories are more successful for enhancing conditional knowledge as compared to passive media (like traditional classroom lectures); according to other studies, they do not significantly differ with respect to declarative knowledge. This means that virtual laboratories can occasionally be as effective as passive media for teaching fundamental chemical facts and ideas (Makransky *et al.*, 2019) [24]. Virtual labs do, however, produce better outcomes when teaching students how to use logic and chemical principles to solve problems (Herga *et al.*, 2015 [15]; Makransky *et al.*, 2019 [24]). The sub-microscopic domain can be dynamically visualized using virtual labs, which also give students an interactive environment (Herga *et al.*, 2015) [15]. This high level of interactivity and visual support for learning engages the learner and helps them comprehend the material more thoroughly (Davenport *et al.*, 2018 [18]; Trindade *et al.*, 2002) [41]. Because passive media helps to reinforce previously learned concepts, combining virtual laboratories with them appears to produce better results (Davenport 2008). Comparing virtual chemical laboratories to conventional hands-on laboratories yields different findings. Comparative studies indicate that, in terms of declarative knowledge, procedural knowledge, and skill-based outcomes, virtual environments are just as effective as hands-on laboratories, if not sometimes even more so. These results are consistent with those of other literature reviews (Sypsas *et al.*, 2018) [34], in which non-traditional and traditional laboratories both produced equivalent or superior results. Despite the frequent contention that virtual laboratories cannot replace conventional, hands-on laboratories (Ikram *et al.*, 2015; Penn *et al.*, 2019; Zhong *et al.*, 2014), there is very little evidence to support this (Faulconer *et al.*, 2018) [13]. This indicates that even in virtual settings with little opportunity for physical interaction, students can acquire technical and laboratory skills (Pyatt *et al.*, 2012) [30]. Learners were able to outperform their peers who received training in the actual laboratory, particularly when procedural guidance was offered during the virtual experiment (Ullah *et al*., 2016) [43]. There is a dearth of studies that evaluate the outcomes of skill-based learning, so more research is needed to examine practical laboratory skills in virtual labs. Thus, despite the media's tendency to portray virtual and physical labs as equally effective, virtual laboratory environments still have the advantage of not requiring a physical lab setting, which saves money, time, and staff resources while facilitating easy accessibility (Brinson, 2015). Additionally, combining virtual laboratories with hands-on labs is a more efficient way to use them, leading to better cognitive and skill-based outcomes. Students' self-efficacy increased significantly when virtual labs were offered as a pre-laboratory exercise compared to a hands-on lab only (Kolil *et al.*, 2020) [20].

Evaluative studies represented the second most frequently used research purpose. Only the experimental group working with virtual chemical laboratories was considered in these studies to assess the participants' affective learning outcomes, with questionnaires serving as the primary evaluation tool, followed by interviews and observations. The results of these empirical studies show that the virtual chemistry laboratories are well-suited for use and that users have a more positive attitude toward chemistry and their own self-efficacy.

Virtual environments are typically regarded by users as satisfying, simple to use, beneficial for learning, and taking less time than actual laboratory work. These favorable responses and opinions show that the teachers and students are comfortable using these systems as a teaching tool for laboratory exercises. But, as was already mentioned, it depends on how each virtual laboratory is set up and designed. Virtual chemical labs with two dimensional "2D"desktop technology have been predominantly employed to offer dynamic visual representation and simulation of chemistry experiments. They can present easily understandable animations that combine the symbolic, microscopic, and macroscopic levels of a chemical system. It is feasible to conduct experiments without a real laboratory setting (Yaron *et al.*, 2010) [47]. However, one disadvantage is that 2D representations cannot provide accurate laboratory environments or real-world lab skills (Ali *et al.*, 2020) [3]. Despite this lack of realism, they have been applied repeatedly over time to large populations. They could be less resource-intensive than more sophisticated 3D VR systems in terms of computer performance and internet bandwidth (Ali *et al.*, 2020) [3].

Many publications have made use of 3D desktop technology. Compared to 2D desktop laboratories, these virtual chemical labs were created with more accurate and realistic representations of the lab settings and equipment. Students can freely explore the virtual laboratory and interact with 3D objects (Qvist *et al.*, 2015 [31]; Winkelmann *et al.*, 2017) [44]. Before participating in actual laboratory activities, students can benefit from using virtual chemical laboratories with a higher level of realism and engagement to get a feel for the space (Tarng, 2017) [36]. The ability to simulate hazardous events that would otherwise be too risky to experience in real life is another application for realistic simulations. As a result, it is possible to identify unsafe laboratory handling and teach proper laboratory procedures in a virtual setting without endangering actual students (Dholakiya *et al.*, 2019 [11]; Makransky *et al.*, 2019) [24]. However, because rendering 3D objects with multiple polygons and simultaneous real-time user interactions is expensive, virtual chemical laboratories in a 3D environment demand more processing power (Dholakiya *et al.*, 2019 [10]; Tarng *et al.*, 2017) [36].

Immersive VR technology has recently started to show promise as a teaching aid for online chemical laboratories. In contrast to 3D desktop, which is only considered a low-immersion technology due to the external screen, HMD VR devices provide a high level of immersion that gives the sensation of truly "being there" in a virtual laboratory environment (Buttussi *et al*., 2018) [7]. Studies found no difference in the efficacy of declarative knowledge between an immersive VR virtual lab, passive media, and a hands-on laboratory (Dunnagan *et al*., 2019 [12]; Makransky *et al*., 2019 [24]). Immersive virtual reality may not be the best method for imparting declarative knowledge, but it may be more useful for training lab participants in emotional and behavioral skills (Makransky *et al*., 2019) [24].

The physical authenticity of the virtual chemical laboratory can also be improved by combining visual display output technology with NUI input devices. Using sensors on portable hardware (such as data gloves or haptic suits), these NUI devices can detect human gestures or the human body visually (such as with Leap Motion or Kinect). It is possible to interact with virtual objects ergonomically and realistically using these cutting-edge tracking technologies (e.g., grabbing, pinching, pouring, etc.). (Al-Khalifa, 2017 [1]; Jagodziski *et al*., 2017). Several studies reviewed in this article performed chemical experiments using visual-based NUI devices (Aldosari *et al*., 2016 [2]; Han *et al*., 2017; Wu *et al*., 2019) [46]. By placing the user's body inside the virtual laboratory environment, the Kinect® NUI device has also been used to enhance presence and immersion (Desai *et al*., 2017) [9]. When using visual-based NUI technology, there are still some drawbacks to be resolved, such as the inability to accurately capture delicate hand gestures and the inability to sense (touch or smell) virtual objects (Wu *et al*., 2019) [46]. The ability to accurately replicate real-world chemical laboratories and practical skills in a virtual environment is made possible by the combination of NUI technology and immersive VR devices (Wu *et al*., 2019) [46].

We investigated how learning theories and instructional support have been applied in virtual environments in this literature review. A common criticism of studies of educational technology is that they frequently ignore learning theories (Hew *et al*., 2019). Integration of instructional design features is considered essential, particularly with the use of VR technologies (Makransky *et al*., 2019) [24]. Unfortunately, because most of the publications under review did not specify a learning theory, the findings of our literature study could not refute this claim. Because they can describe, clarify, and forecast how people will learn when utilizing technologies, learning theories are crucial (Hew *et al*., 2019). The learning theories that were mentioned in the studies reviewed most frequently referenced inquiry-based learning. Virtual chemical laboratories have elements that make them interactive and learner-centered, making them constructive learning environments. Hence, the student can develop a more thorough understanding of chemical concepts (Tatli *et al*., 2012) [37].

The instructional support that the learner receives throughout the virtual learning experience is another facet of instructional design. Efficient learning in virtual settings can be hampered by the learner's cognitive overload, as demonstrated in the study by Makransky *et al*. (2019) [24]. Studies that have conducted value-added research on instructional support principles can teach us more about these features, even though most of these studies have only mentioned them briefly. These studies suggest that virtual environments are most successful when instruction is provided close to the learning content using an audio source and when guidance is provided only as needed (Ullah *et al*., 2016) [43].

Conclusion

In this review of the literature, virtual laboratories for chemistry education are examined in terms of published research. The current study builds on earlier studies in this field because it focused on the value of virtual labs in chemistry education while also conducting a thorough analysis of novel systems and instructional strategies. Even though several publications have argued that virtual environments cannot be substituted as a replacement (Penn *et al*., 2019; Sypsas *et al*., 2018 [34]), the review's findings show that they are viable as a useful complementary tool or as an alternative to hands-on laboratories. In comparison to traditional passive technology (such as text or videos), virtual labs can produce better learning outcomes across all learning domains (cognitive, affective, and skill-based), and they are thought to be just as effective, if not more so, than actual hands-on laboratories. Combining virtual labs with passive media or hands-on labs is more efficient on are examined in terms of published research.

Virtual laboratories can range from 2D visuals to more complex 3D simulations of the actual lab. Even though immersive VR and 3D desktop have seen more use than 2D desktop and 2D desktop, respectively, each of these technologies has advantages of its own and serves distinct needs. To instruct chemical reactions, one may choose a simple, low-cost 2D virtual lab or a more complex, high-cost 3D virtual lab that replicates experiments with straightforward interactions. Immersive VR techniques and NUI input devices are options for achieving the highest level of realism. Most studies, according to this review, have not taken instructional design principles or learning theories into account. These components are necessary to effectively manage the cognitive load of the learner and to offer adequate support when a learner is having trouble. Researchers, teachers, and instructional designers may find this literature review helpful for implementing efficient technologies and instructional design constructs that are based on empirical studies on virtual chemical laboratories. Even though they can't provide the same real-world training and expertise as real laboratories with the technology we have today, virtual laboratories are still useful tools for distance learning. Particularly for circumstances where the only choice is distance learning, such as pandemic outbreaks, schools that cannot afford the cost of real laboratories, or people who are unable to attend specific laboratory sessions.

Limitations

Because they are not fully virtual and still require a physical space in the real world, augmented reality was not included. Data from evaluative and comparative studies were not quantitatively compared in-depth. A systematic meta-analysis is required to determine the effect size of the effectiveness of virtual chemical laboratories.

Competing interest

The authors declare that they have no competing interest.

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