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Article

A comparative study on the suitability of virtual labs for school chemistry experiments

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SUMMARY

Even though the concept of the virtual lab is nearly two decades old now, it has started to gain popularity over the last few years. Teachers and students have been using virtual labs to complement experiments done in physical labs or have even used them exclusively based on the circumstances. Demand for these online simulations reached a new height during the worldwide lockdown due to the COVID-19 pandemic. As schools were closed and thus also physical labs, virtual labs became the only mode of conducting experiments for many students. In this study, we addressed the suitability of virtual labs for school chemistry experiments and compared their effectiveness first qualitatively by focusing on both physical and human resources, convenience, cost, safety, and time involved. Then we assessed the effectiveness of virtual labs quantitatively for the topic 'matter' and compared that with the traditional physical lab experiments. We also acknowledged the unique features of virtual labs to understand concepts that are difficult or impossible to visualize in regular physical labs, including molecular arrangement, movement of individual molecules, and different atomic models. Our quantitative assessment based on pre-test and post-test revealed that students' fundamental understanding improved after intervention through virtual labs, as evident from the t-test.

INTRODUCTION

Experiments are crucial for learning science and help students to understand different concepts more efficiently, to enhance their lab skills, and to promote their critical thinking skills (1, 2). As a result, students move away from rote memorization, grasp the fundamentals of a subject, analyze the observations, and in turn, improve their problem-solving skills. This is even more appropriate for a subject like chemistry, where hands-on experiments are integral parts of the learning process. Hence, much emphasis is given to experiments while learning chemistry, starting from the middle and high school levels (3, 4). Unfortunately, access to physical labs had been limited or temporarily suspended since 2020 due to the COVID-19 pandemic. As a direct result, students could not learn through hands-on experiments, hindering their process of understanding. This can negatively impact learning, particularly in chemistry, where experiments go hand-in-hand with theoretical knowledge. To overcome this, instructors all over the world have explored numerous alternatives for traditional physical labs, including the use of 'virtual labs' (5-7).

Virtual labs are online platforms where users can perform experiments in the form of online simulations (5-7). They are interactive platforms where the output of the experiments can change based on the input provided by the users. Virtual labs have different apparatus, equipment, and instruments that students can use, similar to physical labs, albeit in simulated form. In most of these online simulations, students begin by reading the 'theory' portion to gain theoretical knowledge, understand the learning objectives, and learn background information on the topic. Students then perform the online simulation by themselves, analyze the observations, and learn through their experience. To guide the students through the simulations, information through texts or videos about the equipment and how to use it are provided along with the simulations.

At present, there are quite a few virtual labs suited for middle and high school chemistry courses available; some of these are free and open source, including PhET, Labster (app version), OLabs, and CK-12, while others, including Beyond Labz, Labster (web version), and Praxilabs, are behind a paywall (8-11). In this study, our focus was only on these open-source virtual labs that can be accessed universally and are suitable for middle and high school students. The major advantages of sophisticated, paid subscription virtual labs are the quality of the simulations, coverage of advanced topics, realistic graphics, and the immersive experience to keep the students engaged. On the other hand, most of the open-source virtual labs are more simplistic in nature and may lack sophisticated 3-D graphics, but they provide some essential simulations and can be accessed by anyone anywhere for free.

The hypothesis we wanted to test in this study was whether virtual labs could be deemed an effective, alternative way of learning science from the students' perspectives. Online simulations, if properly explored, have the potential to be an extremely useful tool for remote learning. We wanted to assess if virtual labs can facilitate students' learning by providing them critical access to online experiments. To examine this, we first carried out qualitative analyses for a few chemistry topics. Then we used pre- and post-tests to assess and quantify the effectiveness of virtual labs for the topic 'matter' before and after intervention through simulations, respectively. First, we dissected qualitative aspects of the suitability of virtual labs, which implied that the online simulations can effectively complement the physical lab experience and can even be better than physical labs for certain topics. Our quantitative assessment also revealed that intervention through online simulations helped the students understand several chemistry concepts significantly better. From these findings, we concluded that virtual labs can indeed become an integral tool for distance learning.

RESULTS

We selected five topics (matter, properties of gases, acids-bases, atomic structure, and chemical reactions) to compare the suitability and the efficacy of online simulations for school chemistry experiments. n this section, we conducted comparative analyses for several topics mentioned above, and the usage of these simulations and their benefits. Then we administered pre-test and post-test to assess and quantify the effectiveness of virtual labs for the chapter 'matter'.

Comparison between physical and virtual labs for the topic 'matter'

The topic 'matter' covers several important sub-topics like states of matter, change of states, types of matter, atoms, and molecules. We used both physical lab activities and online simulations to train the students in an experiential way for these sub-topics. For example, to demonstrate 'change of state' in a physical lab, students heated ice cubes first at room temperature in a beaker resulting in liquid water (melting), and then heated the water at 100 °C to convert it to steam (boiling). Reversely, putting a lid on boiling water demonstrated condensation, and keeping liquid water in the freezer (below 0 °C) demonstrated freezing. But it was not possible to visualize the changes in the arrangement of the water molecules through this activity. This was where we wanted to utilize online simulations to facilitate student learning. PhET had some simulations where students could visualize the arrangement of the particles in a particular state and how it changes with temperature and pressure (**Figure 1**). This also helped in visualizing the inter-particle distances for different states of matter and, in turn, could be related to inter-particle forces. Labster is a more sophisticated virtual lab that provides a highly immersive experience, where students can feel like they are in actual labs. Sometimes, a story was woven around the experiment to keep the students interested in a particular topic. Labster offered slightly advanced simulations for 'states of matter' and included concepts like latent heat, specific heat, and heating curve, to name a few.

CK-12, an online platform, offered a basic version of change of state simulation. CK-12 also offered a simulation based on the ideas of elements, compounds, and mixtures. OLabs was another virtual lab that offered a simulation to distinguish between a compound and a mixture (FeS vs. Fe+S) based on their appearances, magnetic properties, the action of heat, and chemical properties. Students also learned about different types of solutions, and different separation techniques. Doing all of these experiments in a physical lab required many resources, time, and teachers' uninterrupted supervision and, of course, were very expensive. Moreover, due to the constraint of time and resources, often these activities ended up becoming group activities rather than individual ones. But in the case of virtual labs, students went

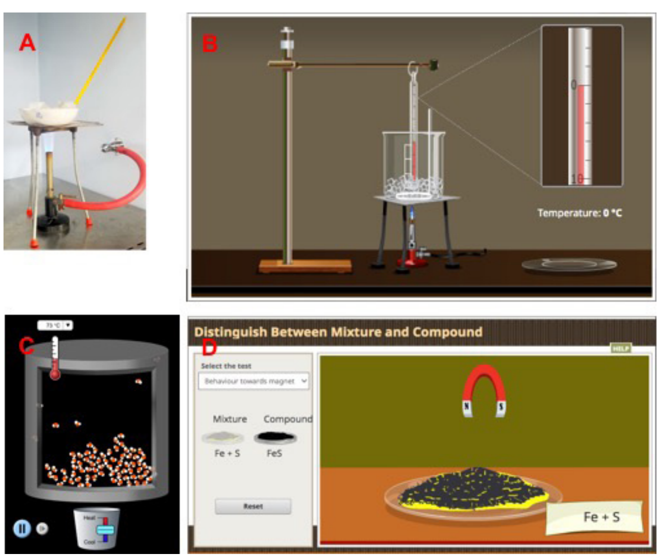

Figure 1. Physical and Virtual experiments conducted for the topic 'matter'. A) Melting of ice experiment in physical lab. B) Melting of ice in virtual lab (OLabs) (10). C) Change in the arrangement of water molecules with increase or decrease in temperature (PhET) (8). D) Simulations on mixtures and compounds (OLabs) (10).

Features	Physical lab	Virtual lab
Location/Platforms	Laboratory facilities at Prayoga Institute of Education Research	PhET, Labster, CK-12, OLabs
Nature of activity	In groups of 2-4	Individual
Time allotted for 'change of states of matter'	30 minutes – 1 hour	Unlimited (students' own time and pace)
Concepts of atoms/molecules/elements/compounds	No physical activities, taught through chalkboard	Through interactive simulations
Physical Resources	Bunsen burner, fuel gas (propane), thermometers, ice, water, tripod stand, wire gauge, evaporating dish, various glassware, inorganic chemicals, organic chemicals and solvents, household grocery and stationary products, etc.	Computer or smartphone, and steady internet connection
Human Resources	Teachers/facilitators/instructors (knowledge and time)	Minimal supervision by teachers as it is mostly student-centric
Personal Protective Equipment (PPE)	Provided for each student	Not needed/virtual PPE is provided
Expenses	Relatively expensive due to the cost of all the materials	No additional expenses as the above-mentioned virtual labs are free

Table 1. Comparison between physical lab and virtual lab for the chapter 'matter'.

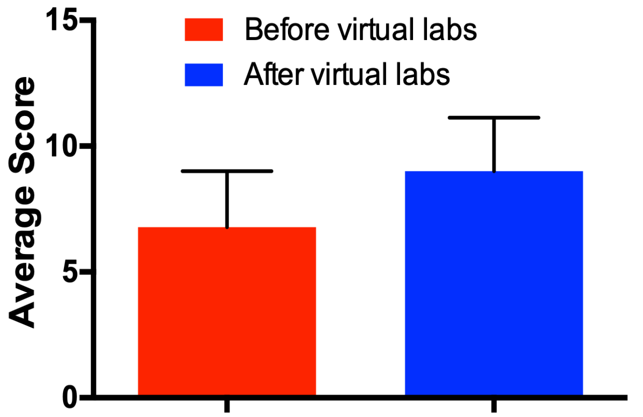

Figure 2. Average score of the students increased after intervention through virtual labs. The increase from a score of 6.78 ± 2.22 to 9.00 ± 2.14 was found to be statistically significant (n = 9, t-test, p value = 0.0096).

through these simulations at their own pace and performed all the experiments individually with unlimited virtual resources (**Table 1**).

Effect of virtual labs on middle school students

To assess the impact of virtual labs on students' conceptual understanding, we conducted a small-scale research project on middle school students (grade 7, n = 9). In this study, we conducted two tests before and after the intervention (total marks for both the tests were 15). The intervention was done in the form of online simulations, where students carried out different simulations based on the chapter 'matter', before answering the post-test. An external facilitator validated and approved the question sets for both the tests. We observed that the average score increased from 6.78 ± 2.22 to 9.00 ± 2.14 after the intervention (**Figure 2**). Students were also able to write the descriptive questions in a coherent and logical way, which could be a reflection of a better understanding of the subject. A t-test conducted on these two data sets revealed that the difference was statistically significant (p value = 0.0096) and clearly showed an improvement.

Virtual lab activities based on properties of gases

PhET offered two virtual labs on the behavior of gases – namely, 'Gases Intro' and 'Gas Properties.' Under these labs, the students performed different simulations aimed at helping them understand how the variables could influence different gas properties and identified the relationship between them. (**Figure 3A**). Students also observed the mixing of gases, collision between the gas molecules, and the diffusion phenomenon. Students altered the number of gas molecules, volume, pressure, and temperature with utmost control, analyzed their observations, and deduced their inferences. Students could also change the number of particles, mass, and radius of the particles, and the temperature and observe how the diffusion process changed. In physical laboratories, it was extremely difficult to demonstrate the Gas Laws and help the students visualize the change in the arrangement of the gas particles with gradual changes in the external parameters. It also required a wide range of experimental arrangements that were difficult to implement in a school setup. This is where virtual labs stepped in and helped the students through interactive simulations.

Virtual lab activities based on acids and bases

'Acids-bases' is another critical chemistry concept that students sometimes find tough to grasp. For this topic, PhET offered two simulations, namely 'pH scale', and 'acid-base solutions.' Students performed various activities and learned important acid-base related topics, such as pH, dissociation, and equilibrium, to name a few (**Figure 3B**). Students could check the pH of a wide range of pre-populated liquid substances (macroscopic level) and determine the concentration of the H_3O+ and OH- ions present in those solutions (microscopic level). Students then observed the dissociations of water, weak and strong acids, and weak and strong bases in solution and verified the pH using a pH meter or pH paper with a color key. Students viewed the constituents of different solutions either by qualitative pictorial representation or by graphical representation depicting the equilibrium concentration. Then they measured the pH of an unknown solution by modulating the initial concentration and strength of the acids or bases. Labster and OLabs also offered similar simulations for pH determination and strength of acids and bases.

Virtual lab activities based on chemical reactions

As schools were closed due to the lockdown caused by the COVID-19 pandemic, access to physical labs was prohibited during the course of teaching the chapter 'chemical reactions'. But encouraged by the success of virtual labs in other chapters and positive feedback from the students, we adopted virtual experiments as modes of experiential learning for 'chemical reactions.' We chose OLabs as a mode of conducting virtual chemical reactions as it offered a wide range

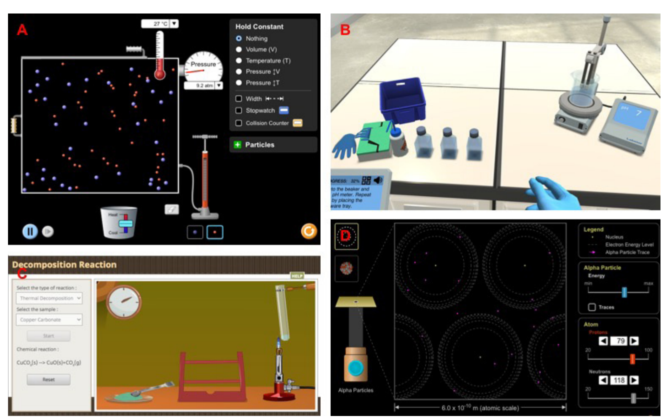

Figure 3. A) Simulations on gas laws (PhET) (8). B) Simulations on acid-base concepts (Labster) (9). C) Representative simulation of a chemical reaction (OLabs) (10). D) Simulations on Rutherford and Thomson models (PhET) (8).

of online simulations for chemical reactions (combination, decomposition, displacement, exo/endothermic reactions, conservation of mass, metal reactivity series) (**Figure 3C**). Students first learned the theory through distance learning (online teaching), followed by virtual chemical reactions performed at home.

We performed a thorough analysis on the effects of virtual simulations, and evaluated using three methods: traditional grading, a rubric to measure higher-order thinking skills and concept mapping. For traditional grading, the average score increased from 35.67 ± 5.77 (pre-test) to 56.25 ± 6.21 (post-test), which was statistically significant (t-test, *p* value = 0.0008). The average score for the concept map also increased from 5.42 ± 1.56 (pre-test) to 7.17 ± 1.19 (post-test), which was again statistically significant (t-test, *p* value = 0.0006) (12). The data clearly showed the positive impact virtual labs made on students' understanding, when accessing physical labs was impossible.

Virtual lab activities based on atomic structure

'Atomic structure' involves the concept of atoms, subatomic particles (electrons, protons, neutrons), and other associated topics, like orbitals and electronic configurations, to name a few. These topics appeared to be abstract for the students, as they could not feel or experience actual atoms or subatomic particles (13,14). Hence, the students leaned atomic structure through chalkboard, presentations, and model kits (whenever deemed appropriate). Unfortunately, often this did not convey an accurate image to the students, and they failed to visualize and understand the structure and components of an atom. Moreover, the students sometimes were unable to appreciate the dynamic nature of an atom. Students also faced difficulties in understanding different atomic theory models, like those of Dalton, Thomson, Rutherford, and Bohr) (13-15).

These challenges faced by students are where virtual labs had clear advantages over physical ones. Using PhET, students built atoms by manually adding protons, electrons, and neutrons and observed the stability, mass number, and charge of the system they formed. They could also correlate their formed models with the actual elements from the periodic table to identify the actual elements. In another simulation, students could form isotopes and calculate the average atomic mass. They tested different atomic model theories which gave them a clear idea about the dynamic nature of atoms. These interactive simulations explained very clearly the features of several atomic models (Thomson's model in PhET, Rutherford's model in PhET and OLabs, Bohr's model and quantum model in Labster) (**Figure 3D**).

Students' feedback

To understand how the students perceived virtual labs, we provided a feedback form to each student. We asked six opinion-based questions on a scale of 1 to 5 and two open-ended questions for this evaluation. It was observed that the vast majority of the students found virtual labs beneficial

Questions	Ratings selected by the students (%)					
	1	2	3	4	5	Average
Virtual Lab simulations helped me to learn about atoms and molecules	0	0	11.1	55.6	33.3	4.2
Virtual Lab simulations helped me to understand change of states of matter	0	11.1	0	44.4	44.4	4.2
Virtual Lab simulations helped me to understand the arrangement of the particles in three different states of matter	0	11.1	11.1	33.3	44.4	4.1
Virtual Lab simulations helped me to understand the movement of the particles in three different states of matter	0	0	11.1	33.3	55.6	4.4
Virtual labs can fully replace the physical labs	44.4	44.4	11.1	0	0	1.7
Virtual labs cannot fully replace the physical labs, but it can complement the physical labs	0	11.1	22.2	11.1	55.6	4.1

Table 2. Survey feedback from the students on the usefulness of virtual labs. The rating scale ranged from 1 to 5 with 1 being the lowest and 5 being the highest. (n = 9).

(rated 4 or 5) for learning a wide range of fundamental topics under 'matter' (**Table 2**). At the same time, students were aware that virtual labs cannot replace physical labs altogether, as 88.8% of the students opted for a response of 1 or 2 for this particular question. However, it is quite clear that virtual labs can complement the learning from physical labs and can effectively step in whenever conducting experiments in a physical lab becomes practically challenging. For the open-ended questions, some of the representative answers were: 'I would actually prefer both virtual and physical labs. They are equally important to me. For some topics such as the atom and bonds we need virtual labs.'; 'I hope that people will not replace physical labs with virtual labs, but find a balance between them.' On the other hand, some students had reservations about virtual labs, as the following response showed: 'I would prefer physical labs because I would understand the concept better. Virtual labs only show how the experiment would look like in real life.'

DISCUSSION

It was quite evident that all the virtual labs used in this study were extremely valuable for the students and help them understand all five topics chosen for this study. For the topics 'matter' and 'chemical reactions', we tested students' learning and assessed using a pre-test (after chalk-and-board teaching) and post-test (after intervention through virtual labs). Our data showed significant improvement in students' learning for both the topics, as confirmed by the t-tests. For the topic 'matter', the average score of the students improved from 6.78 ± 2.22 in pre-test to 9.00 ± 2.14 in post-test, with a p-value of 0.0096, making it statistically significant.

'Matter' is one of the most fundamental topics in chemistry and a good grasp of this is critical to have a sound understanding of other areas built on this. The major subtopics that were dealt with under 'matter' in this study were – mass and volume, states of matter, change of states, atoms, molecules, elements, compounds, and mixture. Even though students generally understood the concept of mass and volume through simple activities and demonstrations, sometimes it was difficult for them to understand the arrangement of the particles in different states of matter and how the arrangement changed from one state to another. Students and teachers had to rely on chalkboard, simple models, or videos to discuss inter-particle distances and inter-particle forces. But, online interactive simulations helped the students to visualize and assimilate these concepts effectively and efficiently. For elementary and middle school students, sometimes it was a little tough to grasp the concepts of atoms, molecules, elements, compounds, and mixtures at the beginning. In physical labs, students learned about these concepts through chalkboard, videos, or ball-and-stick models. But virtual labs added dynamic nature to these activities, where students built molecules from atoms and checked their shapes and polarities based on the substituents and nature of the bonds (PhET). Students also understood the concepts of inter-particle separation and force quite clearly with the help of online simulations. This was especially useful to explain unintuitive observations, such as ice floating on water, as normally solids are heavier than their liquid counterparts.

The comparative study based on teaching the chapter 'matter' clearly demonstrated that virtual labs can complement physical lab activities efficiently and this was confirmed by the improvement in students' understanding level as assessed by the quantitative evaluation (**Figure 2**). At times, it was even possible to use only the virtual labs instead of the physical labs, depending on the topics to be taught and learned.

'Properties of gases' were another important topic where students were introduced to the behaviors of gases and the laws dictating their properties (commonly known as the Gas Laws). Students learned about the effects of various parameters (volume, temperature, pressure, and number of gas molecules) on gas properties and how the properties could be explained by Gas Laws, such as Boyle's Law, Charles' Law, and the Ideal Gas Law. Some slightly advanced concepts, such as thermal equilibrium, the average speed of the particles, and kinetic energy, could also be taught through these simulations. Under Labster, the simulation proceeded through a story-telling scenario involving organ transfer and offered a more sophisticated setup, which was difficult to avail in normal laboratories. Through simulations offered by Labster, students had the option of experimenting with gas thermometry and formulating the Ideal Gas Law.

The concept 'acids-bases' provided the students ample flexibility to learn this important topic through both hands-on activities and online simulations. Even though a lot of the acid-base related activities mentioned earlier can be performed in the physical labs as well, dealing with acids and bases (particularly strong ones like HCl, H_2SO_4, and NaOH) was always a safety hazard, even more so for school-aged students. Students also worked with a variety of chemicals or materials (acids and bases, fruit and vegetable extracts, vinegar, baking soda, and indicators, to name a few), that were expensive. Since acids and bases were corrosive and hazardous, proper infrastructure, PPE, and glass apparatus were needed. Indicators like phenolphthalein and methylene blue are known to cause cancer and other diseases. Most of these activities were time-consuming as well, resulting in them being group activities rather than individual ones. Even though the group activities could be beneficial for the students in developing skills such as working as a team or learning from each other, it could be challenging for certain other aspects. For example, individual activities made students assume more accountability and they needed to complete all the activities paying full attention throughout the activities.

'Atomic structure' was one of the main concepts that paved the way for understanding concepts like stability, reactivity, bonding, and chemical reactions. Students needed to have a thorough and clear understanding of the structure of atoms. But since it was a relatively abstract concept and difficult to conduct experiments at the school level, virtual labs were perfect alternatives for a topic like atomic structure, where students learned about the structures of atoms and different atomic models excellently using online simulations. Our evaluation based on a pre-test and a post-test before and after these virtual labs indicated that the students' understanding of chemical reactions significantly improved after intervention through virtual labs.

This study clearly demonstrated how beneficial virtual labs can be in the domain of chemistry education at the school level. Students not only experienced an alternative form of experiential learning through online simulations, but also learned and understood in depth some of the topics, which they otherwise found difficult. In addition to the experiments, virtual labs offered by Labster also provided a detailed simulation on lab safety, which is an integral component of any chemistry-related experiments. In the future, the efficacies of virtual labs will be analyzed in comparison to the physical ones in a thoroughly quantitative manner for other important chemistry topics such as acids-bases. Moreover, some other sophisticated and realistic virtual labs can be explored in future studies which will tell us if the nature of the virtual labs can also influence students' learning processes.

MATERIALS AND METHODS

General

As this study was centered around human subjects (students), prior consents were sought and obtained from the parents of these students. To understand students' opinions on virtual lab experiences, we opted for a feedback survey from the students involved. The questions asked in this survey can be found under the appendix section.

Physical Labs

All the physical lab experiments were carried out at Prayoga Institute of Education Research (PIER) facilities (Bengaluru, India) over a period of four years (2018-2021) by the same set of12 students (from the school 'Samvida', Bengaluru, India), starting from grade six and continuing till grade nine. All the experiments were closely observed and supervised by the teachers and supervisors. The facilitators informed the students about the possible lab hazards and lab safety protocol, and the students strictly followed proper safety guidelines for all the experiments. Students conducted these experiments either individually or in groups of 2-3, depending on the nature of the experiments. The lab activities or the experiments were chosen from five topics – matter, properties of gases, acids-bases, atomic structure, and chemical reactions.

Virtual Labs

We chose the online simulations carefully after evaluating the suitability of each for the topic at hand. All the online simulations used in this study were available from open-source virtual labs (PhET, Olabs, Labster (app), and CK12) [8,9,10,11]. A comprehensive list of the virtual experiments conducted by the students can be found in the Appendix section. 9 students from grade seven, who were not part of the physical lab activities, took part in online simulations based on the same topics mentioned under the 'physical labs'. All 9 students completed all the simulations provided to them. These students were part of the school 'Samvida' (Bengaluru, India) and the online activities and classes were conducted at Prayoga Institute of Education Research (Bengaluru, India). The facilitator first demonstrated a few online simulations to the students and then the students completed all the simulations all by themselves. If the students had any doubts or faced any technical issues with the simulations, the instructor guided them through the troubleshooting process – either through video meeting or in person.

Pre-test and Post-test

For the topic 'matter', we conducted the pre-test after the traditional chalk-and-board teaching. Then students completed a series of online simulations on the same topic. Post-intervention through virtual labs, we conducted the post-test. Both the pre-test and post-test consisted of different types of questions – fill in the blanks, 'true' or 'false', multiple choice questions (MCQs), and two open-ended questions. The questions asked in the post-test were different from the pre-test.

Statistical Analysis

Plotting and t-tests (paired, two-tailed) were performed using Prism 6 (GraphPad, San Diego, USA). A p value less than 0.05 was considered to be statistically significant.

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REFERENCES

1. Holmes, N. J. et al. "Teaching Critical Thinking". *Proc. Natl. Acad. Sci. U.S.A.*, vol. 112, no. 36, 2015, pp. 11199-11204. doi: 10.1073/pnas.1505329112
2. Whitehurst, G. J. "The Value of Experiments in Education". *Educ. Finance Policy*, vol. 7, no. 2, 2012, pp. 107-123. doi: 10.1162/EDFP_a_00058
3. Babinčáková, Maria, et al. "Online Experimentation during COVID-19 Secondary School Closures: Teaching Methods and Student Perceptions". *J. Chem. Educ.* vol. 97, no. 9, 2020, pp. 3295–3300. DOI: 10.1021/acs.jchemed.0c00748
4. Rodriguez, Jon-Marc G., et al. "Modifying Laboratory Experiments to Promote Engagement in Critical Thinking by Reframing Prelab and Postlab Questions". *J. Chem. Educ*. vol. 95, no. 12, 2018, pp. 2141–2147. doi: 10.1021/acs.jchemed.8b00683
5. Hawkins, Ian et al. "Virtual laboratory vs. traditional laboratory: which is more effective for teaching electrochemistry?". *Chem. Educ. Res. Pract.*, vol. 14, 2013, pp. 516-523. doi: 10.1039/C3RP00070B
6. Winkelmann, Kurt et al. "A Study of High School Students' Performance of a Chemistry Experiment within the Virtual World of Second Life". *J. Chem. Educ*. vol. 91, no. 9, 2014, pp. 1432–1438. doi: 10.1021/ed500009e
7. Wieman, C. E. et al. "A powerful tool for teaching science", *Nat. Phys.*, vol. 2, 2006, pp.290-292. doi: 10.1038/nphys283
8. PhET: Free online physics, chemistry, biology, earth science and math. *PhET*. phet.colorado.edu. Accessed 20 Nov. 2021
9. *Labster*, Copenhagen, Denmark. labster.com. Accessed 20 Nov. 2021
10. OLabs (Ministry of Electronics & Information Technology, India). *OLabs*. olabs.edu.in. Accessed 20 Nov. 2021
11. *CK-12*. ck12.org/student. Accessed 20 Nov. 2021
12. Senapati, S. Anand, S. A. A. "Promoting Higher-Order Thinking Skills Based on Thinking-Based-Learning Coupled with Experiential Learning Pedagogy Using Open-Source Virtual Labs for Online Classes". *Manuscript submitted*, 2022
13. Park, E. J. et al. "Identifying Atomic Structure as a Threshold Concept: Student mental models and troublesomeness". *Int J Sci Educ*. vol. 31, no. 2, 2009, pp. 233-258. doi: 10.1080/09500690701675880
14. Zarkadis, N. et al. "Studying the coherence of students' portrayed representations of the atomic structure - Connections with conceptions and misconceptions". *Science Education International*. vol. 32, no. 2, 2021, pp. 164-171. doi: 10.33828/sei.v32.i2.10
15. Zarkadis, N. et al. "Studying the consistency between and

within the student mental models for atomic structure". *Chem. Educ. Res. Pract.*, vol. 18, 2017, 18, pp. 893-902

Appendix

Survey Questions:

1. Please rate your experience from a scale of 1 to 5 for the first six questions.

a) Virtual Lab simulations helped me to learn about atoms and molecules

b) Virtual Lab simulations helped me to understand change of states of matter.

c) Virtual Lab simulations helped me to understand the arrangement of the particles in three different states of matter.

d) Virtual Lab simulations helped me to understand the movement of the particles in three different states of matter.

e) Virtual labs can fully replace the physical labs (i.e. I do not need physical labs, only virtual labs are enough).

f) Virtual labs cannot fully replace the physical labs, but it can complement the physical labs (i.e. I'll prefer both virtual labs and physical labs while learning)

2. Would you prefer virtual labs or physical labs while learning chemistry topics? Justify in 2-3 sentences.

3. What improvement would you like to see regarding the usage virtual labs for learning science?

List of all the virtual lab experiments conducted for this study:

Matter:

phet.colorado.edu/en/simulations/build-a-molecule

phet.colorado.edu/en/simulations/states-of-matter-basics

phet.colorado.edu/en/simulations/states-of-matter

interactives.ck12.org/simulations/chemistry.html

www.labster.com/simulations/states-of-matter-new

amrita.olabs.edu.in/?sub=73&brch=2&sim=70&cnt=1

phet.colorado.edu/en/simulations/gases-intro

Properties of Gases:

phet.colorado.edu/en/simulations/gas-properties

labster.com/simulations/ideal-gas-law-introduction-new

labster.com/simulations/ideal-gas-law-apply-to-save-a-life-new

Acids-Bases:

phet.colorado.edu/en/simulations/ph-scale

phet.colorado.edu/en/simulations/acid-base-solutions

labster.com/simulations/acids-and-bases-principles

labster.com/simulations/advanced-acids-and-bases

amrita.olabs.edu.in/?sub=73&brch=3&sim=6&cnt=1

Chemical Reactions:

amrita.olabs.edu.in/?sub=73&brch=2&sim=77&cnt=1

amrita.olabs.edu.in/?sub=73&brch=2&sim=118&cnt=1

amrita.olabs.edu.in/?sub=73&brch=3&sim=79&cnt=1

amrita.olabs.edu.in/?sub=73&brch=3&sim=80&cnt=1

amrita.olabs.edu.in/?sub=73&brch=3&sim=81&cnt=1

amrita.olabs.edu.in/?sub=73&brch=3&sim=82&cnt=1

amrita.olabs.edu.in/?sub=73&brch=3&sim=59&cnt=1

cdac.olabs.edu.in/?sub=75&brch=12&sim=92&cnt=1

Atomic Structure:

phet.colorado.edu/en/simulations/build-an-atom

phet.colorado.edu/en/simulations/isotopes-and-atomic-mass

phet.colorado.edu/en/simulations/rutherford-scattering

cdac.olabs.edu.in/?sub=75&brch=12&sim=88&cnt=1

labster.com/simulations/atomic-structure-principles-2