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Enhancing Chemical Engineering Education: The Role of Virtual Labs in Bridging Theory and Practice

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ABSTRACT

The implementation of Virtual Laboratories (V-Labs) in chemical engineering education provides valuable improvements to learning to work in Physical Laboratories (Ph-Labs). This article discusses the effect of Virtual Laboratories (V-Labs) (https://www.labster.com/, https://www.vlab.co.in/) on 120 second-year undergraduate chemical engineering students studying in the CHEM2000 course at the Sohar University. The students participated in a series of six V-Lab simulations, followed by additional Ph-Lab experiments that focused on elementary engineering chemistry and safety. A structured Likert-scale questionnaire, in addition to qualitative data from open-ended questions, was used, and SPSS were used for its analysis. Results were positive, with 98% of students also indicating that V-Labs were a valuable pre-lab training tool, and training on them contributed to their understanding of safety, procedures, and analytical skills. Additionally, 97% felt more confident and better prepared for physical lab sessions after use of V-Labs. There was a significant change in the students' attitude after the V-Lab intervention, as evidenced by the statistical analysis ($p = 0.009$), which reinforces the effectiveness of using V-Labs to bridge the preparedness gap. Students appreciated the possibility of repetition in simulations and the opportunity to safely explore complex matter (though some abilities, such as dealing with operations, are best gained through hands-on experimenting), implying that a blended learning strategy is required. The results of the study are in favour of incorporating V-Labs in traditional lab exercises to promote students' conceptual understanding, confidence, and engagement in engineering education.

Keywords: Virtual labs; chemical engineering education; laboratory simulation; student perception; engineering pedagogy

INTRODUCTION

Educators encourage students of all ages to engage in scientific investigation. Science, Technology and Engineering (STE) inquiry-based learning, in which students conduct experiments, offers several advantages over conventional curriculum instruction. Students can connect directly with the natural world using scientific instruments, data collection procedures, models, and concepts. The classroom or the laboratory can be used for research. Computer technologies now enable investigations to conduct inquiries utilising simulated resources and instruments via V-Labs. While Ph-Lab are acknowledged mainly as essential for STE and engineering education, the efficiency of virtual, simulated labs is debated.

Although physical and virtual laboratories can attain comparable objectives, such as exploring scientific principles, enhancing collaborative skills, boosting motivation for scientific knowledge, and developing inquiry abilities, each possesses unique advantages.

Students can learn practical laboratory skills, such as troubleshooting, by using physical equipment. They can also learn about students' difficulties when planning experiments that need a thorough equipment setup and long-term observation. According to cognitive STE ideas, the ability to use sensory input is another benefit of Ph-Lab (Husnaini et al. 2019; Diez et al. 2025).

Students can learn about scientific issues by responding to unexpected events, such as experimental errors. Inquiry skills and conceptual knowledge can be developed through PhD investigations. Contextual knowledge can help students develop scientific concepts while also providing them with practical laboratory experience and skills. Conversely, V-Labs can expedite learning by emphasising critical information and eliminating unnecessary dimensions (Li & Liang 2024). Using a virtual platform also facilitates the explanation of specific situations. Students can conduct more experiments and collect more data in less time than a genuine experiment, and at a reduced cost (Woner et al. 2022).

Using simulation-based learning laboratories, students can actively participate, solve problems, and communicate in a simulated environment (Beatrice et al. 2024). Zamiri & Esmaeili (2024) emphasize the importance of hands-on activities for skill development, while Ryker and McConnell (2017) highlight the challenges of procedural adherence in traditional labs. Virtual laboratories (V-Labs) have emerged as transformative tools, enhancing accessibility and engagement, as noted by Deriba et al. (2024) and Wang et al. (2025). These platforms can supplement physical labs, improving educational quality and inclusivity (Goudsouzian et al. 2018). The COVID-19 pandemic accelerated the adoption of V-Labs, revealing mixed student responses but maintaining performance standards (Johnson and Barr 2021). Research indicates that blended learning models, integrating virtual and physical labs, can enhance understanding and engagement (Hurtado-Bermúdez and Romero-Abrio 2023). Longitudinal Future studies should focus on the long-term effects (4 years) of V-Labs on learning outcomes and the development of effective pedagogical strategies for their integration into curricula.

V-Labs enable students to interact more effectively with the curriculum in a comfortable and realistic environment, thereby enhancing their chances of success. 3D virtual environments also enable total immersion and realistic interaction within a virtual world grounded in scientific principles. These elements can shift learning from passive instruction to active exploration, repetition, and rapid feedback (Seifab et al. 2020). This method enables students to explore, interact, and learn more effectively (Parong et al. 2018).

However, constructing an efficient V-Lab is a highly involved process, including implementing multiple components, such as interactive interfaces and visualisation, as well as instruction. Often, the complexity of such development fails to meet the specified targets. In this view, Wastberg et al. (2019) recognised critical challenges in developing V-Labs, which strongly affect their performance and utility in generating knowledge in education as a pedagogical approach. In line with this, to promote optimal learning in a bioprocess engineering laboratory component of a biotechnology course within the chemical engineering curriculum, this study was undertaken to assess the effectiveness of this pedagogical technique in improving learning and enhancing laboratory skills.

To achieve this, open-source V-Labs experiments in engineering chemistry were adopted from an open resource, where students (120) can learn the basics of laboratory safety and the principles of engineering chemistry. Subsequently, the virtual Engineering Chemistry laboratory was assessed and compared for its effectiveness as a supporting aid for a Ph-Lab activity.

METHODOLOGY

PARTICIPANTS

The course contents of the Chemistry for Engineers course (CHEM2000), a level 2 core course (4 credits) in the Bachelor of Chemical Engineering curriculum at the Sohar University, are meticulously crafted to connect essential chemical principles with engineering applications. This curriculum emphasizes practical, application-oriented chemistry relevant to fields such as materials science and process engineering. The course covers organic chemistry, focusing on molecular structure and reaction mechanisms, alongside physical chemistry topics like thermodynamics and electrochemistry. Hands-on laboratory sessions enhance theoretical knowledge through practical experiments, fostering critical thinking and problem-solving skills. By aligning chemistry with engineering learning outcomes, CHEM2000 prepares students for advanced studies and real-world challenges, ensuring they are well-equipped for their future careers in engineering. The participants for this study were 120 second-year undergraduate chemical engineering students (108 Female and 12 male all Omani nationals) enrolled in the academic year 2021-2022.

CHEM2000 LABORATORY COMPONENT

CHEM2000 introduces students to the fundamental principles of intermolecular forces, liquid properties, hydrocarbons, various functional groups, and the synthesis of products, as well as reaction mechanisms. It is organised around functional groups, simple reaction mechanisms, and organic synthesis. The course is designed to equip students with practical skills that they can apply in real-world scenarios.

The Course Learning Outcomes (CLOs) are:

1. Explain the relative forces between molecules, types of solutions, mixtures and phases diagrams
2. Discuss surface tension phenomena and relative viscosity to intermolecular forces
3. Describe the properties of solutions that are colligative properties and the process of osmosis
4. Draw structural formulas for hydrocarbons, name hydrocarbon molecules, and discuss the methods for preparing alcohols, ethers, aldehydes, ketones, acids, and amines
5. Calculate gas solubility, colligative properties, equilibrium constants, enthalpy, etc., using Henry's law, van 't Hoff's equation, and the equation of state.
6. Demonstrate the phenomena of surface tension, viscosity, colligative properties, principal methods of polymer formation and synthesis of alcohols and ethers.

However, in the CHEM2000 laboratory component, students study organised research techniques using analytical instruments. It facilitates transdisciplinary learning and decision-making. Lab work is usually done in groups. In a lab, teamwork requires planning, problem-solving, and achieving results. Experimentation is encouraged, as it helps students to overcome and learn from their mistakes, thereby improving their cognitive abilities and making them feel encouraged and motivated.

V-LAB

Chemistry for Engineering V-Lab experiments were selected to meet students' needs for a better understanding of engineering chemistry fundamentals. In the virtual laboratory, students were exposed and asked to perform six different lab experiments to cover laboratory outcomes of the CHEM200 course. In a V-Lab, students must follow the instructions provided during the laboratory and

complete the survey questions and also provide qualitative feedback, after completing the experiments. As shown in Table 1, the survey questions were designed using the four-level Likert response scale to evaluate the learning outcomes. There were four response options: strongly disagree (SD), disagree (D), agree (A), and strongly agree (SA)

PH.-LAB

The basic goals of the hands-on laboratory were similar to the virtual laboratory experiment. Before performing the experiments, students were asked to identify the major steps and devise a work plan among the group member to assure an equal portion of the responsibilities. To perform the six experiments, students were divided into groups. After completion of Ph-Lab, students were asked to participate in Ph-Lab survey. As shown in Table 2, sixteen statements were constructed using the four-level Likert response scale to determine the effect of V-Lab on the effectiveness of Ph-Lab and learning outcomes.

TABLE 1. V-Lab Experiment

Experiment No	Objective	Virtual Lab Experiment*
1	Lab safety simulation	https://rb.gy/8gvpll
2	Determine the absolute viscosity of organic liquids	https://rb.gy/gbkz69
3	Identify the functional groups	https://rb.gy/w91ljb
4	To estimate the amount of glucose	https://rb.gy/qvifgv
5	To determine hardness, alkalinity, and COD	https://rb.gy/pxsyib
6	To determine unknown concentration using various titrimetric methods.	https://rb.gy/u3pvp7
7	To obtain pure components using Fractional distillation.	https://rb.gy/sytmvo
8	To separate Organic compounds using Column Chromatographic	https://rb.gy/gpnz87

*Free on email registration, ("These experiments and labs will be hosted for open access through the main project website www.vlab.co.in")

TABLE 2. Survey questionnaire on V-Lab and Ph-Lab

Gained a better understanding of lab safety, what to do in the event of an accident, & how to file an accident report.
V-Lab explains lab safety, followed by Ph-Lab, which is useful for understanding lab safety.
V-Lab experiments aid in the understanding of CHEM2000.
V-Lab helps understand the effect of parameters on the outputs.
V-Lab facilitated in the results analysis and interpretation.
V-Lab step-by-step procedure helped conduct accurate experiments.

V-Lab instilled confidence to do a lab experiment accurately without an instructor has improved.
V-Lab experiments are easy to perform and easy to use.
V-Lab is useful and effective as a pre-lab learning tool.
V-Lab complements the Ph-Lab
The V-Lab facilitated the execution of successful Ph-Lab experiments.
V-Lab Improved confidence in experiments in a Ph-Lab
List virtual lab elements that would be challenging to replicate in the Ph- lab
List any Ph-lab competencies that would be difficult to execute in a V-Lab.
List ways of improving the Ph lab session.
List ways of improving the V-lab experiences.

ANALYSIS

The faculty subsequently devised a template to collect students' perceptions of *V-Lab* and *Ph-Lab*. An online survey, approved by the University's Institutional Planning and Development, was written and administered in English to students enrolled in the CHEM2000 course at the end of the 2020-21 second semester. To evaluate whether there is a substantial difference between students' perceptions in the V-Lab and Ph-Lab, a statistical tool (SPSS Statistics) was used. The qualitative data from students' reflections on learning (both *V-Lab* and *Ph-Lab*) were rigorously analysed.

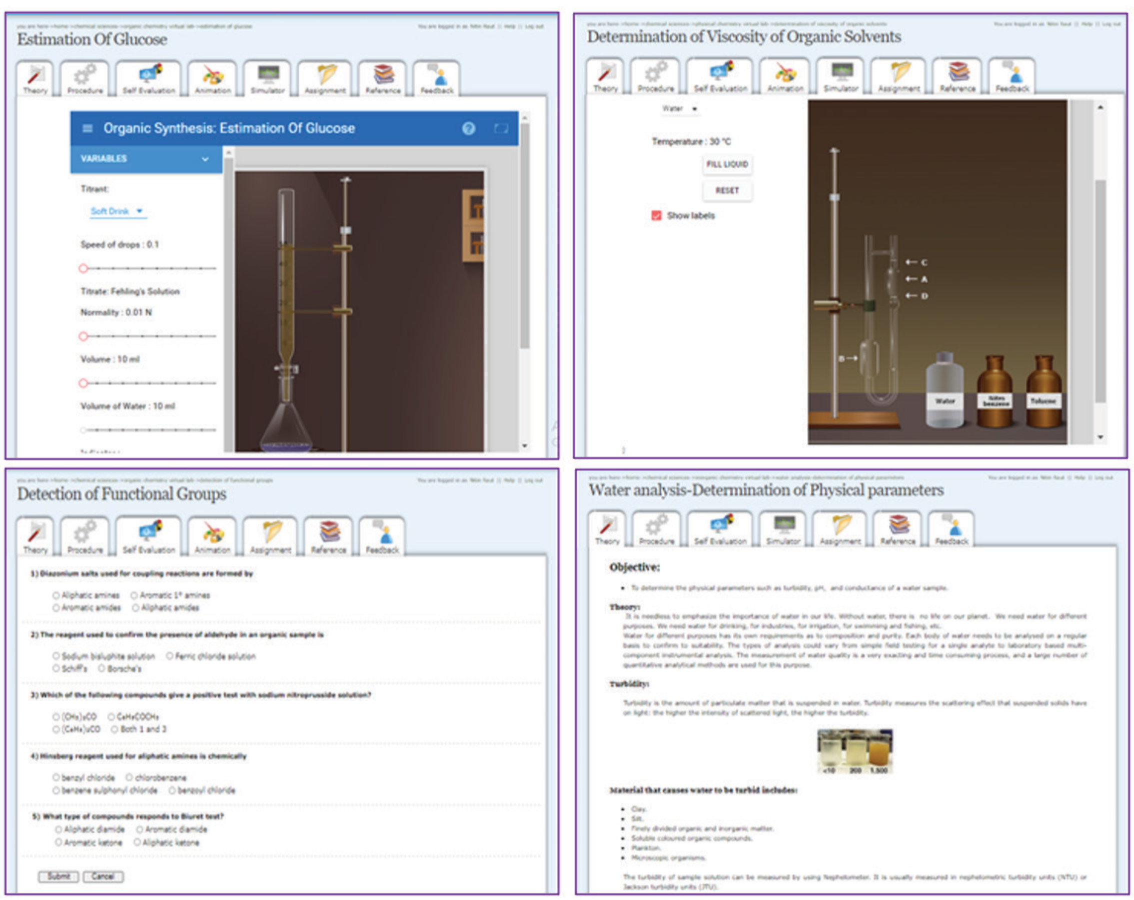


FIGURE 2. V-Lab Experiments (www.vlab.co.in, An Initiative of Ministry of Education Under the National Mission on Education through ICT, Govt. of India)

V-LAB SIMULATIONS FOR SAFETY

Safety induction is a common practice that allows students to operate safely within the laboratory. The lab technician typically distributes a series of documents before introducing students to the lab. As a result, this approach is often misconstrued and considered perplexing, as it does not provide students with sufficient knowledge and awareness. Students are learning about safe principles and practices in an immersive environment through the virtual safety lab simulator.

Multiple-choice questions and demonstrations allow students to identify realistic solutions to hazards. The participants were expected to respond to statements in the simulation laboratory survey in order to evaluate CHEM2000's health and safety component. The evaluation survey was designed to monitor the effectiveness of the course's aims and objectives, specifically the laboratory component outcomes, delivery, resources, and student experience. The ethical approval, a testament to the integrity and ethical standards of our research, has been obtained from the Sohar University Research Ethics Committee.As illustrated in Fig. 3, students unanimously agreed that virtual laboratories assist students in developing an understanding of laboratory safety (https://rb.gy/8gvpll).

DISCUSSION

In recent decades, active learning and assessment have been encouraged in various ways. Students learn by solving real-world problems. This study examined the practicality and usefulness of virtual laboratory experiments in conjunction with a physical engineering laboratory to enhance students' understanding of CHEM2000 concepts, laboratory safety standards, experimental design, and data analysis. Students were entrusted with conducting a Virtual experiment and devising a pH-Lab technique. Except for 2%, over 95% of students (80% agreed and 15% strongly agreed) claimed they could become familiar with equipment, procedures, and safety precautions by completing the safety V-Lab.

FIGURE 3. V-Lab simulation for safety principle & practice (https://www.labster.com/simulations/lab-safety/)

Comparison of responses was done to investigating the impact of V-Labs on students' confidence in completing experiments before and after participating in Ph-Lab labs. Students' Ph-Lab responses were statistically varied, with a p-value of 0.009, indicating a significant difference. Lack of knowledge and expertise hampers Ph-Lab experiments significantly. (Seifan, 2019). Educating students so they can learn from CHEM2000 lab experiences is fundamental.

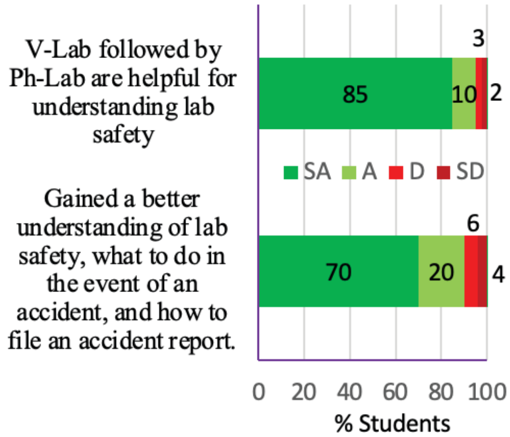


FIGURE 4. Students' perceptions of safety

98 % of participants supported V-Lab as a pre-lab training (Figure 4 and 5), as it teaches the basics, methods, preparation, and implementation. Students can watch interactive videos to prepare for the lesson. However, they lack the competence to conduct rigorous lab tests. Hence, their results often contradict textbooks. Students reported that the virtual laboratory was engaging and had clear objectives. Virtual labs outperform traditional pH-Lab studies for unobservable phenomena.

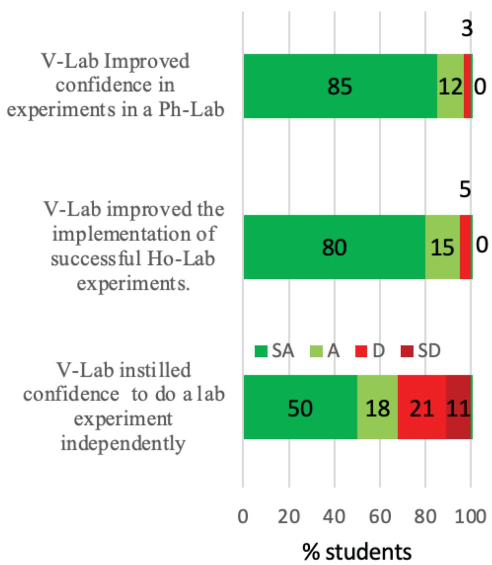
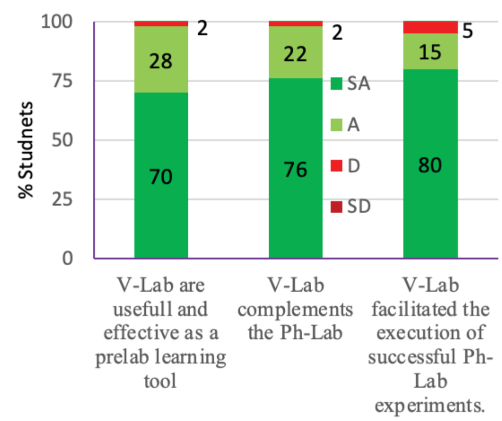


FIGURE 5. Students' perceptions of the importance of the V-Lab in developing confidence

Comparing students who used only traditional technology to those who completed virtual experiments improved understanding. Students can apply complex inquiry methods to challenging independent variables using virtual experiments in Ph-Lab.

Virtual labs provide students with the opportunity to study unobservable phenomena, which are phenomena that cannot be directly observed in a physical laboratory setting. These could include processes that occur at a molecular level or in extreme conditions. This unique feature of virtual labs allows students to gain a deeper understanding of these phenomena, which are often crucial in engineering and science education. 97% of the students believed that the V-Lab helped them feel more comfortable and confident in carrying out the Ph-Lab, and increased their problem-solving skills, critical thinking, experimentation skills, and capacity to apply their knowledge in practical situations.



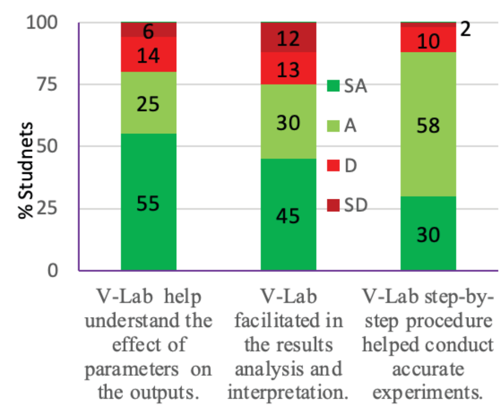


FIGURE 6. (a) & (b) Students' perception on effectiveness of V-Lab

75% of the students agreed that using V-Lab made it easier to interpret the results because it allowed them to conduct more experiments and simulate the effects of different parameters. Virtual experiments produce precise data that promotes conceptual learning. This study found that students who participated in virtual chemistry activities outperformed their peers in terms of fundamental knowledge (Kanwal et. al., 2021).

Virtual labs provide students more time to investigate and understand concepts than live labs. Virtual labs benefit students in the same way as actual labs. Overall, these results align with Sellberg et. al, (2024). According to the survey of students who participated in a simulated laboratory, 68% agreed that virtual laboratory practice enhanced their confidence in completing laboratory work, whereas 97% reported increased confidence after attending a real-world laboratory (Figure 3).

However, when students were asked whether the simulation laboratory supplements the hands-on practices before and following the Ph-Labs laboratory, there was no statistically significant change in their response (p-value 0.657). Other variables, however, have a significant role in the performance of virtual laboratories. Concerns like usability, clarity, technology, and design are inextricably linked to the difficulty of building a functional virtual system. Usability refers to how easy the system is to use, clarity to how well the system's interface and instructions are understood, technology to the tools and software used, and design to the overall structure and layout of the virtual lab. Thus, developing or selecting a virtual lab experiment is not uncomplicated, and process development is an iterative process consistent with the finding reported by Wastberg et. all (2019).

88 % of the students agreed or strongly agreed that the virtual engineering laboratory made learning the fundamentals of CHEM2000 much easier by allowing them to conduct experiments and compare the results without worrying about running out of time, materials, or safety precautions. This increased confidence and comfort in using virtual labs is a testament to their effectiveness and should reassure educators and researchers about their potential. Both physical and virtual laboratories offer benefits and drawbacks. Students can readily study unobservable phenomena not observed in Ph-Lab experiments and conduct further experiments that are impossible in a physical context. Physical laboratories are crucial when students are expected to gain a comprehensive understanding of science, including practical skills and the ability to analyse erroneous data. Students expressed concern that the time spent waiting for solutions to be generated and evaluated in the Ph-Lab could have improved their ability to complete the tasks, despite the importance of the Ph-Lab.

Students regarded the Ph-lab as particularly valuable and efficient due to their prior exposure to the fundamentals in the V-Lab (Figure 6 and 7). This enables students to gain more knowledge while increasing their motivation and involvement. Students can complete more repetitions of experiments in V-Labs than they would in the Ph-Lab due to the speedy execution of methods. Furthermore, obtaining evaluation and feedback from a diverse range of students with various educational backgrounds will be extremely valuable in determining whether the virtual laboratory was a success and in making any necessary improvements.

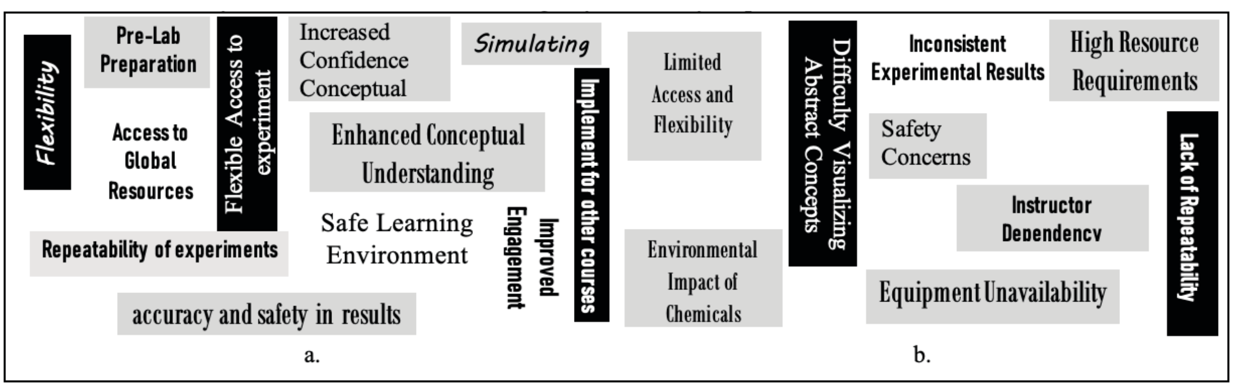


FIGURE 7. Qualitative Feedback-Students' perception of the V-Lab (a.) and Ph-Lab (b.)

CONCLUSION

The V-Lab and the Ph-Lab have been successfully linked into the chemical engineering curriculum, playing a crucial role in enhancing students' understanding of engineering chemistry principles and concepts. It is recommended that both laboratories be paired because they have been demonstrated to be incredibly effective at actively engaging students in various learning environments and approaches.

This active engagement not only makes the learning process more dynamic but also makes the students feel more involved and participative. Students' feedback on V-Lab has been overwhelmingly positive, serving as a testament to its effectiveness. 88 % reported an increased understanding of CHEM2000 fundamentals after using the virtual engineering lab.

97% felt that the safety V-Lab improved their knowledge of potential risks and the steps they could take to lessen those hazards. Students found that V-Lab helped them evaluate results by allowing them to do more experiments and simulate diverse situations.

Importantly, 98% of participants approved using V-Lab trials as pre-lab training, demonstrating the students' confidence in and acceptance of the virtual labs. Students overwhelmingly stated that V-Lab helped them improve their ability to solve problems, think critically, conduct experiments, and apply what they learned in the classroom.

Compared to Ph-Lab experiments, V-Lab experiments offer a cost-effective solution, underscoring their practicality. They enable students to examine unobservable processes while also doing inexpensive and quick experiments. This cost-effectiveness reassures about the practicality of the virtual labs. For chemical engineering students, developing V-Lab experiments may offer an emerging resource for establishing a safe, engaging, and interactive environment that supports their academic careers in better understanding a range of topics.

The optimal strategy combines virtual and real-world experiences. As a result, virtual laboratories are not designed to replace in-person instruction but rather to augment it and function as a helpful alternative when necessary.

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DECLARATION OF COMPETING INTEREST

None.

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