Research Article

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# The role of virtual laboratories in advancing student learning on acid–base equilibrium

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**Abstract:** This study investigated the effectiveness of integrating virtual laboratories into secondary school chemistry instruction on acid–base equilibrium concepts in Addis Ababa. It examined the impact of simulation-based virtual laboratories on students' academic achievement, conceptual understanding, engagement, and skill development. PhET Interactive Simulations, a free platform developed by the University of Colorado Boulder, was used for its multilingual support, device compatibility, and suitability for resource-limited schools. A quasi-experimental, mixed-methods design involved 66 Grade 12 students divided into an intervention group and a comparison group. The comparison group completed traditional curriculum-guided laboratory activities, while the intervention group supplemented these experiments with virtual pre-lab simulations. For instance, in an acid–base titration exercise, intervention students used simulations to predict pH changes before performing the experiment, whereas the comparison group proceeded directly to hands-on work. Quantitative analysis using pre- and post-tests revealed statistically significant improvements in the intervention group, although the effect size was small (Cohen's $d$ = 0.16), likely due to the short intervention and modest sample size. Qualitative interviews indicated that virtual laboratories enhanced engagement, understanding, and collaboration despite occasional access challenges. Overall, virtual laboratories can effectively complement traditional instruction when software accessibility and equitable technology use are ensured.

**Keywords:** virtual laboratory; acid–base equilibrium; chemistry education; mixed-methods; secondary schools; student engagement

## 1 Introduction

Chemistry education, like many areas of STEM, continues to face challenges in making complex scientific concepts accessible and engaging for students. Among these, acid–base equilibrium is particularly difficult, as it requires not only theoretical understanding but also practical experimentation to fully grasp dynamic chemical reactions. In many schools, especially in developing contexts such as Ethiopia, instruction relies heavily on teacher-led explanations with limited hands-on laboratory experiences. This limitation is frequently due to logistical barriers such as insufficient laboratory facilities, costly equipment, and safety concerns.[1–3] Consequently, students often lack meaningful opportunities for practical engagement, negatively affecting their conceptual understanding and enthusiasm for chemistry.

Recent advances in educational technology offer potential solutions to these challenges. One promising tool is the virtual laboratory – an interactive, computer-based platform that simulates real laboratory experiments in a safe and controlled environment.[4] Virtual laboratories allow students to manipulate variables, observe chemical reactions, and analyze data without the physical constraints of traditional labs. For example, in acid–base titration exercises, students can simulate the gradual addition of a titrant to a solution and observe corresponding pH changes digitally before performing the hands-on experiment. Research shows that virtual laboratories

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promote active learning, enhance conceptual understanding, and develop critical thinking skills.[5,6] Despite these advantages, their use in Ethiopian classrooms remains limited, and empirical evidence on their effectiveness in resource-constrained settings is scarce. Furthermore, many studies fail to describe the type of virtual laboratory software used, its accessibility (free vs. licensed), or compatibility with different devices, which is critical for schools with limited technological resources.[7–10]

Given these circumstances, it is important to investigate whether virtual laboratories can enhance students' comprehension of acid–base equilibrium, support collaborative learning, and improve practical skills development. This study explores the integration of virtual laboratories into secondary school chemistry instruction, using a mixed-methods approach that combines quantitative performance measures with qualitative reflections, providing a comprehensive understanding of their impact on student learning.

## 1.1 Rationale for studying this topic

The rationale for this study stems from several interrelated considerations in chemistry education, educational technology, and curriculum development. First, traditional chemistry instruction often does not provide adequate hands-on experience, particularly in Ethiopian schools where resource shortages limit laboratory functionality. Acid–base equilibrium, which involves dynamic chemical reactions and variable manipulation, is especially difficult to teach effectively through lecture alone.[3]

Second, virtual laboratories provide an accessible and scalable alternative. These platforms create interactive, simulated environments where students can safely perform experiments regardless of geographic location or school resources.[11,12] Students can repeatedly access experiments at their own pace, enhancing conceptual understanding in ways rarely possible in traditional laboratory settings.[13] In this study, the PhET Interactive Simulations platform, developed by the University of Colorado Boulder, was selected for its open-access availability, recognition in chemistry education, compatibility with PCs, tablets, and smartphones, and minimal technical requirements, making it suitable for resource-limited schools.

Third, virtual laboratories offer opportunities for collaborative learning, allowing students to discuss predictions, analyze results together, and plan experiments collaboratively. These interactions reflect socio-cultural learning principles and can differ significantly from collaboration in traditional labs, where group work may be limited or overshadowed by teacher demonstrations.

Fourth, while the theoretical benefits of virtual laboratories are well documented, empirical evidence on their actual impact in specific contexts, such as Ethiopian secondary schools, is limited.[14] Investigating virtual labs' effect on acid–base equilibrium learning provides evidence for their integration into curricula and offers guidance for educators and policymakers. Finally, this study aligns with global priorities to modernize STEM education, promote equity, and ensure quality instruction. By examining virtual laboratories' educational value, the research contributes to innovation in chemistry education and addresses gaps in access, engagement, and academic achievement.[2]

## 1.2 Research questions

This study is guided by the following research questions:

(1) How does student performance in understanding acid–base equilibrium differ between those who use virtual laboratories and those who engage in traditional hands-on laboratory experiments?
(2) What are the perceptions and experiences of students regarding the effectiveness of virtual laboratories in enhancing their understanding and practical skills in acid–base equilibrium?
(3) How do virtual laboratories support collaboration among students, and in what ways do these collaborative interactions differ from those in traditional laboratory settings?

### 1.3 Theoretical framework

The theoretical framework for this study integrates multiple educational and psychological perspectives to explain how virtual laboratories can enhance student learning outcomes in acid–base equilibrium education. At its foundation is Constructivist Learning Theory, which posits that learners actively construct knowledge through experience and interaction with their environment.[15–18] Virtual laboratories align with this theory by providing students in the intervention group with interactive, hands-on experiences where they can manipulate experimental variables, observe chemical reactions, and analyze outcomes. For example, in acid–base titration simulations, students can explore the effect of gradually adding a titrant on solution pH, predicting the endpoint before performing the actual hands-on experiment. This active engagement allows learners to build personal, meaningful understandings of complex chemistry concepts, bridging the gap between abstract theory and practical application.[18]

Complementing this is Experiential Learning Theory, which emphasizes that learning is most effective when it involves concrete experience followed by reflection.[19] Virtual laboratories provide immediate, concrete experiences through simulated experiments that students can repeat and revisit, enabling reflection on decisions and outcomes. In the intervention group, this iterative process encourages students to analyze their predictions, compare them with actual results, and refine their understanding of equilibrium dynamics. In contrast, the comparison group, which relies solely on traditional laboratory experiments, may have fewer opportunities for such structured reflection due to limited exposure and the constraints of one-time hands-on activities.[19]

The Technology Acceptance Model (TAM) further informs the framework by explaining how perceptions of usefulness and ease of use influence engagement with technology.[20] In this study, TAM helps examine whether students in the intervention group perceive virtual laboratories as accessible, user-friendly, and beneficial for enhancing their understanding of acid–base equilibrium. Positive perceptions are expected to motivate greater interaction with the simulations, thereby improving learning outcomes compared with the comparison group, who do not have access to this digital tool.[20]

Finally, a Socio-Cultural Perspective emphasizes the importance of social interaction and collaborative learning in cognitive development.[21] Virtual laboratories act as cultural tools that facilitate peer collaboration and guided exploration. In the intervention group, students work in pairs or small groups within the simulation environment to discuss experimental strategies, analyze discrepancies between predictions and outcomes, and collectively troubleshoot errors. These collaborative practices contrast with traditional lab settings, where group discussions may be limited or dominated by teacher demonstrations. Such interactions help students co-construct deeper conceptual understandings of acid–base equilibrium and reflect real-world scientific collaboration.[22]

Together, these theoretical perspectives provide a comprehensive lens for examining the cognitive, experiential, technological, and social dimensions of virtual laboratory integration in chemistry education. They inform the study design, including the use of pre-lab simulations for the intervention group, the collection of quantitative data to assess conceptual understanding, and qualitative interviews to capture collaborative learning and student experiences. By grounding the research in these interrelated theories, the study ensures a holistic assessment of virtual laboratories' educational potential in both intervention and comparison contexts.

## 2 Literature review

### 2.1 Virtual laboratories in acid–base equilibrium education

Chemistry education often faces challenges in providing comprehensive practical experiences due to resource limitations, logistical barriers, and safety concerns associated with traditional laboratory work. These challenges are particularly evident in complex topics such as acid–base equilibrium, where hands-on experimentation is crucial for reinforcing theoretical concepts.[23] Virtual laboratories (VLs) have emerged as effective tools to address these constraints, offering interactive, immersive simulations of real-world experiments in digital environments.[4,24,25] VLs allow students in the intervention group to manipulate experimental variables, observe chemical reactions, and analyze outcomes in safe, repeatable, and widely accessible formats. In contrast, students in the comparison group rely solely on traditional laboratory experiments, which may be limited in scope and frequency due to resource constraints.[2,3]

In this study, the PhET Interactive Simulations platform, developed by the University of Colorado Boulder, was selected as the virtual laboratory tool.[26,27] PhET is freely available, research-based, and widely validated for its effectiveness in promoting conceptual understanding in science education.[26,27] Its compatibility with laptops, desktops, and tablets ensures accessibility even in under-resourced schools, making it suitable for intervention group students to engage in inquiry-based learning without additional financial or technological constraints.

## 2.2 Educational benefits of virtual laboratories

Virtual laboratories provide opportunities for experiential and inquiry-based learning by enabling students to actively engage with experimental procedures. Through manipulation of variables, observation of outcomes, and data analysis, learners construct knowledge in interactive and iterative ways.[6,28] Research indicates that students in intervention groups using VLs often demonstrate higher conceptual understanding and knowledge retention compared to peers in comparison groups engaged in traditional laboratory instruction.[5,29,30] For example, simulated titrations allow students to predict and observe pH changes as a titrant is added, reinforcing comprehension of buffer systems and equilibrium shifts in ways that may be difficult to achieve in conventional labs.

VLs also offer repeated and flexible access to experiments, enabling students to revisit challenging concepts at their own pace.[31,32] Visualizations of phenomena such as ion dissociation and dynamic equilibrium help students grasp abstract chemical principles more effectively. This flexibility supports differentiated learning, accommodating individual learning speeds and needs, which is especially important in resource-limited educational settings where traditional lab access may be inconsistent.

## 2.3 Student engagement and learning outcomes

Virtual laboratories have been shown to significantly enhance student engagement, particularly in challenging topics like acid–base equilibrium.[1,4] Virtual simulations promote inquiry-driven learning, enabling students to test hypotheses, conduct virtual experiments, and reason through trial-and-error processes. These experiences foster critical thinking, problem-solving, and conceptual mastery – skills essential for STEM success.[33,34] In comparison, students in the comparison group may have fewer opportunities for exploratory learning due to the structured, teacher-led nature of traditional labs.

Collaboration is another notable advantage of VLs. Intervention group students working in pairs or small groups can discuss results, jointly analyze errors, and reflect on outcomes, simulating authentic scientific practice.[35–38] These interactions foster socio-cultural competencies such as communication, negotiation, and cooperative problem-solving, which are less emphasized in conventional lab activities. By combining interactive engagement, repeated experimentation, and collaborative learning, virtual laboratories support both conceptual and experiential chemistry education.

## 2.4 Perceptions and experiences of students

Qualitative studies indicate that students hold positive perceptions of virtual laboratories (VLs) in learning acid–base equilibrium.[25,38–40] Intervention group students value the safe, risk-free environment, where mistakes serve as learning opportunities, and repeated experiments enhance both confidence and understanding.[33,41]

Simulations also allow exploration of scenarios that may be unsafe or impractical in traditional laboratories, reinforcing conceptual and procedural knowledge simultaneously.

However, challenges remain. Technical difficulties, unclear instructions, limited real-time feedback, and unstable internet connections can hinder learning. Some students note that VLs cannot fully replace tactile experiences, emphasizing that physical manipulation of chemicals and direct observation of reactions remains essential for developing comprehensive laboratory skills.[31,32] These findings support a blended approach, where students benefit from both virtual and traditional laboratory experiences to maximize learning outcomes.

## 2.5 Empirical evidence on educational impact

Empirical research consistently demonstrates that students in intervention groups using VLs achieve higher cognitive gains than peers in comparison groups relying solely on traditional labs.[42,43] VLs enhance procedural skills by improving data accuracy, strengthening predictive reasoning, and fostering structured experimentation. Longitudinal studies further suggest that knowledge retention is often higher among intervention group students compared to those performing only hands-on labs.[44]

The pedagogical impact of VLs depends heavily on instructional design. Unguided exploration or poorly integrated simulations can limit outcomes, highlighting the need for scaffolding, structured guidance, and alignment with learning objectives.[32] When effectively implemented, VLs complement traditional laboratories, creating engaging and comprehensive learning environments.

## 2.6 Technology acceptance and usability

The effectiveness of VLs is closely tied to student perceptions and interaction with the technology. Studies informed by the Technology Acceptance Model (TAM) indicate that perceived usefulness and ease of use strongly influence engagement and learning outcomes.[45,46] Intuitive interfaces, interactive controls, gamified elements, and guided steps reduce cognitive load and increase motivation, enabling students to focus on conceptual understanding rather than technical challenges.[47,48] Institutional support, including teacher training and curriculum alignment, further ensures sustained and effective use of VLs.[25,49] Without these supports, even high-quality platforms may be underutilized.

## 2.7 Research gap

Despite the global adoption of VLs, several research gaps remain, particularly in the Ethiopian context. Few studies examine VL implementation and impact in Ethiopian secondary schools, where resource limitations pose unique challenges.[38] Many studies lack detailed reporting on software type, device compatibility, accessibility, and cost – factors critical for under-resourced settings.

Additionally, while VLs enhance conceptual understanding, limited evidence exists regarding their role in fostering collaboration and socio-cultural learning. Studies combining quantitative performance measures with qualitative insights into student experiences are particularly scarce. This study addresses these gaps by employing the freely accessible PhET Interactive Simulations platform, compatible with multiple devices, and providing detailed documentation of the intervention group experience. By examining both learning outcomes and student perceptions, this research generates context-specific evidence to guide curriculum developers, educators, and policymakers on VL usability, pedagogical impact, and practical implementation in Ethiopian secondary schools.

# 3 Research methodology

## 3.1 Philosophical stand of the researcher

This study is grounded in a pragmatic philosophical approach, which emphasizes practical solutions and the selection of research methods most suited to addressing real-world challenges in chemistry education. Pragmatism allows the researcher to integrate both quantitative and qualitative methods to capture a comprehensive understanding of students' learning experiences with virtual laboratories. Quantitative methods provide measurable evidence of conceptual understanding and procedural skills, while qualitative methods allow for a nuanced exploration of students' perceptions, engagement, and reflections. This dual approach ensures that both objective outcomes and subjective experiences are represented, providing a holistic understanding of the educational impact of the intervention in real classroom contexts.

The researcher's methodological decisions were guided by principles of active learning, experiential engagement, technology integration, and collaboration. For example, the intervention was designed to provide students with repeated opportunities to manipulate variables, observe experimental outcomes, and reflect on their learning, thereby ensuring that conceptual understanding was reinforced through practice. Structured group interactions encouraged students to discuss predictions, share observations, and collaboratively solve problems during virtual laboratory sessions. These design decisions were informed by the underlying principles of learning, emphasizing that students construct knowledge more effectively when learning is active, reflective, and socially situated.

The choice of a mixed-methods research design was influenced by the need to capture multiple dimensions of learning. Quantitative data were used to measure changes in knowledge and procedural skills, while qualitative interviews provided rich insights into students' experiences, challenges, and perceptions of virtual laboratory use. This combination allowed the researcher to understand not only whether students improved academically but also how they engaged with the learning process, collaborated with peers, and navigated technological tools. The intervention was structured to include pre-lab exploration, hands-on virtual manipulation, and reflective analysis, creating a cycle of active engagement and deeper comprehension. By integrating the intervention into existing curriculum structures and aligning it with classroom instruction, the study ensured that research procedures mirrored authentic educational practice. Overall, the pragmatic stance shaped decisions regarding participant selection, instructional design, data collection, and analysis, prioritizing both measurable learning outcomes and the lived experiences of students engaging with virtual laboratories.

## 3.2 Research design

The study employed a mixed-methods research design, combining quantitative and qualitative approaches to provide a comprehensive understanding of the effects of virtual laboratories on students' learning in acid–base equilibrium. The quantitative component assessed conceptual understanding and procedural skills through standardized pre-tests and post-tests. These assessments enabled a direct comparison between students in the intervention group, who participated in virtual laboratory sessions, and students in the comparison group, who received only conventional instruction. This design allowed for a rigorous evaluation of the intervention's impact on learning outcomes while controlling for baseline knowledge.

The qualitative component consisted of semi-structured interviews conducted with students in the intervention group. These interviews explored students' experiences with virtual laboratories, their perceptions of usability, engagement, collaborative learning, and challenges encountered during the sessions. Qualitative data also provided insights into affective and socio-cultural dimensions, including motivation, peer interaction, and technology acceptance. The integration of both quantitative and qualitative approaches allowed the study to triangulate findings, enhancing reliability, validity, and depth of interpretation.

The mixed-methods design was particularly appropriate for educational interventions, where cognitive, social, and affective factors interact to shape learning outcomes. Quantitative measures offered objective evidence of academic gains, while qualitative insights captured nuanced experiences that cannot be measured through tests alone. For example, interviews revealed how students negotiated understanding with peers, adapted to technological tools, and engaged in inquiry-based problem solving. By combining both approaches, the study addressed not only measurable outcomes but also the rich, experiential dimensions of learning. The intervention group participated in virtual laboratory sessions alongside regular classroom instruction, while the comparison group continued with traditional teacher-led instruction, textbook exercises, and guided "cookbook" experiments. This design ensured that differences in learning outcomes could be attributed to the virtual laboratory intervention rather than to prior exposure to the curriculum.

## 3.3 Research population and sampling procedures

The population for this study comprised Grade 12 chemistry students enrolled in non-government secondary schools in Addis Ababa. Non-government schools were selected because they were more likely to possess the technological infrastructure required to implement virtual laboratory sessions, including functional computers or tablets, reliable internet connectivity, and adequately equipped laboratory facilities. These prerequisites were necessary to ensure meaningful comparisons between virtual and traditional laboratory experiences.

Two schools were purposively selected based on three key criteria. First, they had reliable internet access to allow smooth operation of virtual laboratory simulations. Second, they had sufficient laboratory infrastructure for practical comparisons with traditional experiments. Third, administrators and teachers were willing to participate and facilitate the intervention. Following school selection, random assignment designated one school as the intervention group and the other as the comparison group, minimizing selection bias and enhancing the internal validity of the study.

For qualitative data collection, students from the intervention group were selected using a combination of purposive and convenient sampling. Purposive sampling ensured that participants had significant engagement with virtual laboratories, allowing them to provide meaningful insights into their experiences. Convenient sampling considered practical factors such as availability, willingness to participate, and scheduling constraints. Combining these approaches ensured that qualitative data were both rich and representative of students actively involved in virtual laboratory sessions.

## 3.4 Virtual laboratory description

The virtual laboratory employed in this study was the PhET Interactive Simulations platform, developed by the University of Colorado Boulder. PhET is free, open-access, and research-based software that has been widely validated for its effectiveness in promoting conceptual understanding in science education. Its accessibility makes it particularly suitable for schools with limited laboratory resources, as it allows students to engage with complex experimental concepts even in the absence of fully equipped physical labs. Additionally, PhET is compatible with multiple devices, including PCs, laptops, tablets, and smartphones, providing flexible access for all students in the intervention group and ensuring that technological limitations do not hinder participation.

Within the simulations, students were able to manipulate experimental variables, adjust conditions, and observe immediate visual feedback. In acid–base equilibrium simulations, learners could modify the concentrations of acids and bases, monitor the resulting changes in pH, and visualize the underlying ionization processes in real time. This interactive approach enabled students to actively engage with chemical phenomena that are often difficult to observe in conventional laboratory settings, thereby bridging the gap between theoretical concepts and practical understanding.

PhET's pedagogical design was closely aligned with the study's objectives, allowing students to focus on experimental design, data interpretation, and hypothesis testing rather than becoming preoccupied with technical challenges. The platform's ability to support repeated experimentation encouraged iterative learning, risk-free exploration, and mastery of key chemistry concepts. By integrating PhET simulations into the curriculum, the study provided students with opportunities to reinforce classroom instruction, develop critical thinking skills, and deepen their conceptual understanding, ultimately enhancing the overall learning experience in acid–base equilibrium education.

### 3.5 Intervention procedure

The intervention was implemented over a 6-week period as part of the Grade 12 chemistry curriculum, specifically targeting the topic of acid–base equilibrium. Students in the intervention group participated in weekly virtual laboratory sessions designed to provide hands-on experience with chemical concepts in a safe, interactive, and controlled digital environment. Each session followed a structured sequence comprising pre-lab exploration, hands-on experimentation within the simulation, and post-experiment reflection. During the pre-lab exploration phase, students were introduced to the experimental scenario, familiarized themselves with the virtual apparatus and variables, and made predictions about expected outcomes. This preparatory stage encouraged learners to engage in critical thinking, hypothesize relationships between variables such as acid or base concentration and pH, and consider potential sources of error before conducting the experiment.

The experimentation phase allowed students to actively manipulate variables and observe chemical reactions in real time. For example, in a buffer solution simulation, students could adjust the concentrations of weak acids and their conjugate bases, observe the resulting pH changes, and visualize the equilibrium shifts through real-time ionization diagrams. In a titration simulation, learners could carefully add titrant to a solution while monitoring pH changes on a virtual pH meter, observing equivalence points and the behavior of indicators. These interactive features allowed students to explore complex chemical phenomena that are difficult to replicate or observe accurately in conventional laboratory settings, particularly in schools with limited equipment or safety restrictions. The immediate visual feedback provided by the simulations enabled students to test multiple hypotheses, identify misconceptions, and iteratively refine their procedures, which strengthened procedural competence and conceptual understanding.

Post-experiment reflection was an integral part of the intervention, offering opportunities for collaborative analysis and discussion. Students worked in pairs or small groups to compare their predictions with observed outcomes, interpret discrepancies, and critically evaluate experimental results. For instance, after performing a virtual titration, groups would discuss why the observed pH differed slightly from their initial predictions, considering factors such as dilution effects, ionization constants, and measurement precision. Through these collaborative interactions, students not only deepened their understanding of chemical equilibria but also developed essential socio-cultural skills such as communication, negotiation, cooperative problem-solving, and the ability to collectively analyze scientific data. These group discussions mirrored authentic scientific practice, preparing learners for teamwork in research and professional environments.

Virtual laboratories functioned both as pre-lab preparation tools and reinforcement mechanisms for classroom instruction. By engaging with simulations prior to traditional hands-on experiments, students in the intervention group built conceptual frameworks that reduced cognitive load during physical laboratory work, enabling them to focus more effectively on experimental procedures and data interpretation. The comparison group, on the other hand, continued with conventional instruction, performing experiments individually or in small groups under teacher guidance, using textbook-based exercises and guided "cookbook" approaches. While these traditional labs provided necessary tactile experience, they often limited opportunities for repeated trials, immediate feedback, and iterative learning, which constrained students' ability to self-correct errors and test alternative hypotheses.

One of the key advantages of the virtual laboratory intervention was its ability to integrate immediate feedback and safe risk-free experimentation into the learning process. Students could explore multiple experimental conditions, intentionally make errors, and observe the consequences without the hazards or time constraints associated with physical chemicals and equipment. For example, students experimenting with weak acid-strong base titrations could add excess titrant and immediately observe resulting pH curves and buffer capacity effects, allowing them to understand concepts such as over-titration in a risk-free context. Similarly, in buffer solution experiments, they could test different ratios of conjugate acids and bases to investigate the impact on pH stability and equilibrium shifts. These experiences fostered not only a deeper grasp of theoretical principles but also procedural fluency, analytical reasoning, and confidence in handling experimental processes.

Furthermore, the structured and collaborative nature of the virtual laboratory sessions reinforced peer learning and socio-cultural development. Students engaged in joint decision-making when selecting experimental parameters, provided feedback to one another during simulations, and collectively interpreted results to construct shared understanding. Such collaboration contrasts with traditional laboratory environments where opportunities for discussion and co-construction of knowledge are often limited, as students tend to follow step-by-step instructions or perform experiments individually. By embedding collaboration directly into the virtual learning process, the intervention facilitated critical reflection, discourse, and peer-mediated learning, making students active participants in their knowledge construction.

In summary, the 6-week intervention effectively combined pre-lab exploration, hands-on simulation, and reflective analysis to enhance conceptual understanding, procedural competence, and collaborative skills in acid–base equilibrium. Virtual laboratories provided repeated, flexible, and safe opportunities for experimentation, which complemented classroom instruction and offered experiences that might otherwise be inaccessible due to resource limitations. The integration of feedback, iterative practice, and group discussion not only reinforced learning outcomes but also prepared students for authentic scientific inquiry, demonstrating the pedagogical value of virtual laboratories in modern chemistry education.

### 3.6 Collaboration and socio-cultural learning

Collaboration and socio-cultural learning played a central role in the virtual laboratory experience. The intervention group frequently engaged in pair or small group work, which provided opportunities to discuss procedures, negotiate decisions about experimental variables, and jointly interpret the outcomes of the simulations. For instance, in the buffer solution simulation, students worked together to determine the appropriate concentrations of acids and bases, predict resulting pH changes, and evaluate whether their predictions aligned with observed results. These collaborative engagements not only fostered critical thinking and deeper content understanding but also strengthened communication and problem-solving skills, reflecting the authentic practices of the scientific community. By integrating collaboration into the design of the intervention, students learned to co-construct knowledge, test ideas collectively, and refine their conceptual understanding through peer dialogue.

In contrast, the comparison group primarily engaged in conventional laboratory activities, where opportunities for peer interaction were more constrained. While traditional laboratory instruction emphasized individual or teacher-led experimentation, it often limited students' chances to discuss and interpret data collaboratively. As a result, the co-construction of knowledge and socio-cultural learning experiences were less pronounced. The intervention group, by contrast, not only advanced their technical and conceptual skills but also developed the socio-cultural competencies necessary for effective teamwork. This holistic approach prepared them for participation in professional research contexts and future STEM careers, where collaboration and shared problem-solving are integral to success.

### 3.7 Data collection methods

Quantitative data were obtained through standardized pre-tests and post-tests designed to measure students' conceptual understanding and procedural skills in acid–base equilibrium. These assessments ensured comparability between the intervention and comparison groups, allowing for clear evaluation of learning gains attributable to the virtual laboratory experience. In addition, performance metrics embedded within the PhET simulations provided valuable insights into the intervention group's ability to manipulate experimental variables, accurately record observations, analyze data, and draw valid conclusions. These objective measures offered a direct reflection of students' practical engagement with scientific inquiry in a controlled, technology-enhanced environment.

To complement the quantitative findings, qualitative data were collected through semi-structured interviews with students in the intervention group. The interviews explored perceptions of software usability, levels of engagement, collaborative experiences, and challenges encountered and perceived learning benefits. This qualitative component captured the socio-cultural dimensions of learning that standardized tests alone could not reveal, providing a richer understanding of how virtual laboratories supported both cognitive and interpersonal development. By triangulating quantitative performance measures with qualitative feedback, the study achieved a comprehensive evaluation of the intervention's effectiveness, encompassing not only academic achievement but also the lived experiences and evolving competencies of the learners.

## 3.8 Research instruments

The study employed three primary instruments: standardized tests, virtual laboratory rubrics, and semi-structured interview guides. The standardized tests were carefully developed to measure both conceptual knowledge and practical skills related to acid–base equilibrium, ensuring alignment with the Grade 12 chemistry curriculum. These tests provided a reliable basis for comparing the intervention group, which utilized virtual laboratories, with the comparison group, which continued with traditional instruction. By addressing higher-order thinking, procedural understanding, and problem-solving, the tests went beyond rote recall, capturing deeper levels of student comprehension.

The second instrument, virtual laboratory rubrics, was specifically designed to evaluate students' performance within the simulation environment. The rubrics assessed a range of competencies, including procedural accuracy, effective manipulation of variables, cognitive engagement in problem-solving, and application of logical reasoning to interpret experimental results. Through this structured framework, the study ensured consistent evaluation of learners' interactions with the technology, enabling the identification of strengths and areas for further improvement in scientific inquiry skills.

Finally, semi-structured interview guides provided an avenue for exploring students' lived experiences during the intervention. These interviews invited participants to reflect on their engagement, collaborative interactions, perceptions of the technology's usefulness, and the ways in which the virtual laboratories supported or challenged their learning processes. In doing so, they illuminated aspects of motivation, confidence, and socio-cultural learning that were not easily captured by quantitative measures. All instruments were aligned with the study's theoretical framework, piloted to ensure reliability and validity, and deliberately structured to capture both measurable outcomes and rich experiential data. Together, these instruments offered a holistic approach to understanding the effectiveness of virtual laboratories in enhancing both academic achievement and socio-cultural competencies.

## 3.9 Data analysis procedures

The analysis of data in this study followed a mixed-methods approach, integrating both quantitative and qualitative procedures to ensure a comprehensive understanding of the educational impact of virtual laboratories. Quantitative data obtained from standardized tests and virtual laboratory exercises were analyzed using a combination of descriptive and inferential statistics. Descriptive statistics, including measures such as means, standard deviations, and percentage scores, were first employed to provide an overview of students' performance patterns across both the comparison group and the intervention group. These measures highlighted central tendencies, variability, and the distribution of scores, thereby offering insights into the general trends of achievement.

For inferential analysis, independent-samples *t*-tests were conducted to determine whether statistically significant differences existed between the performance of students in the intervention group and those in the comparison group. This allowed the study to identify the extent to which exposure to virtual laboratories influenced learning outcomes relative to traditional instructional methods. In cases where assumptions of normality or homogeneity of variance were not met, non-parametric alternatives such as the Mann–Whitney *U* test were applied, ensuring the robustness and reliability of the results. These inferential analyses provided a rigorous means of validating the effectiveness of the intervention in fostering conceptual understanding and procedural skills.

Qualitative data collected from semi-structured interviews were analyzed using thematic analysis. The coding process was both deductive and inductive: initial codes were derived from the theoretical framework – including categories such as active knowledge construction, experiential engagement, technology acceptance, and collaboration – while additional emergent codes were incorporated as new insights surfaced from the data. This approach allowed for the identification of recurring themes and patterns that captured students' perspectives, challenges, and reflections on their learning experiences within the virtual laboratory environment.

Finally, triangulation was employed to integrate the findings from quantitative and qualitative strands. By cross-validating statistical results with students' narratives and reflections, the study enhanced the validity and credibility of its conclusions. This multi-layered approach not only confirmed the measurable gains observed in learning outcomes but also revealed the underlying processes and socio-cultural factors that contributed to those improvements. Through this combination of methods, the analysis procedures provided a holistic and nuanced understanding of how virtual laboratories influenced both cognitive and collaborative dimensions of student learning.

## 3.10 Ethical considerations

The study adhered to strict ethical standards throughout its design, data collection, and analysis processes in order to protect the rights and well-being of all participants. Informed consent was obtained prior to participation, both from the students involved in the intervention and from school administrators who granted permission for the study to be conducted within the educational setting. Students were clearly informed about the purpose of the research, the nature of their participation, and their right to withdraw at any point without facing any academic or personal consequences. This ensured that participation was fully voluntary and grounded in respect for individual autonomy.

Confidentiality was a central priority in the handling of all collected data. To safeguard privacy, students' identities were anonymized through the use of codes rather than personal identifiers, and all raw data were securely stored in password-protected digital files and locked storage cabinets for physical documents. Access to the data was restricted solely to the research team, thereby minimizing the risk of unauthorized use or disclosure. These measures provided participants with assurance that their responses and performance outcomes would remain confidential, encouraging openness and honesty in both test performance and interview responses.

Formal ethical approval for the study was obtained from the university's research ethics committee, ensuring compliance with institutional guidelines and internationally recognized principles of beneficence, non-maleficence, and justice. The principle of beneficence guided the research to maximize potential benefits, such as improving teaching and learning practices, while non-maleficence ensured that no harm, discomfort, or risk was imposed upon participants. Justice was maintained by ensuring equitable treatment of all participants, regardless of group assignment, gender, or prior achievement levels.

Incorporating these ethical safeguards fostered a climate of trust and integrity within the study, allowing students to share authentic experiences with the virtual laboratories without fear of judgment or reprisal. By ensuring transparency, fairness, and protection of participant rights, the research was able to generate reliable and meaningful data that not only strengthened the validity of the findings but also contributed positively to the educational community.

# 4 Findings

## 4.1 Quantitative findings

Before analyzing the post-intervention outcomes, the necessary assumptions for parametric testing were verified to ensure the reliability of statistical comparisons. Specifically, normality and homogeneity of variance were assessed to determine whether the independent-samples *t*-test was an appropriate analytical technique. Establishing baseline equivalence between the intervention and comparison groups was considered essential because it confirmed that any observed differences in post-test scores could reasonably be attributed to the virtual laboratory intervention rather than pre-existing variations in student achievement.

The pre-test comparison revealed that students in the intervention group ($n = 32$) achieved a mean score of 61.8 with a standard deviation of 10.4, while those in the comparison group ($n = 34$) recorded a mean score of 57.2 with a standard deviation of 11.4. An independent-samples *t*-test indicated no statistically significant difference between the groups at the pre-test stage, $t(64) = 1.7$, $p = 0.09$. This result suggests that the two groups were academically comparable prior to the implementation of the virtual laboratory intervention, thereby establishing a valid basis for subsequent comparisons (see Table 1).

Following the 6-week virtual laboratory intervention, post-test scores were analyzed to evaluate its impact on students' academic achievement in acid–base equilibrium. The results demonstrated that the intervention group achieved a mean score of 79.41 with a standard deviation of 7.35, whereas the comparison group scored a mean of 72.4 with a standard deviation of 9.63. The independent-samples *t*-test confirmed that the difference in post-test performance between the two groups was statistically significant, $t(64) = 3.43$, $p < 0.001$. This finding indicates that students who were exposed to virtual laboratory activities significantly outperformed their peers who relied solely on traditional instructional methods.

The effect size for this difference, calculated using Cohen's *d*, was 0.16. Although this value corresponds to a small effect size according to conventional statistical guidelines, it nevertheless suggests that the virtual laboratory intervention produced a measurable and meaningful improvement in student performance. The relatively modest effect may be attributed to several factors, including the short duration of the 6-week intervention, the limited sample size, and the relatively strong baseline academic achievement of the participating students. Despite these constraints, the presence of a statistically significant improvement highlights the potential educational value of integrating virtual laboratory tools into chemistry instruction.

In addition to the statistical outcomes, the findings underscore how the virtual laboratory intervention supported active and engaged learning. Pre-laboratory activities allowed students to familiarize themselves with experimental procedures and theoretical concepts prior to classroom instruction, thereby enhancing their preparedness for active participation. The interactive simulations offered repeated opportunities for experimentation, immediate feedback, and visualizations of chemical phenomena, all of which reinforced conceptual understanding and strengthened procedural skills. Moreover, collaborative tasks embedded within the virtual labs encouraged peer discussion, collective problem-solving, and reflective thinking. These socio-cognitive processes contributed to the improved performance observed in the intervention group compared to their counterparts in the comparison group.

As shown in Table 2, students in the intervention group demonstrated superior academic achievement following the virtual laboratory experience. The small but meaningful effect size reinforces the practical significance of virtual laboratories in enhancing students' conceptual understanding and procedural competence in acid–base equilibrium.

**Table 1:** Independent samples *t*-test for pre-test academic achievement scores.

| Group | N | M | SD | *t* | *p*-Value |
|---|---|---|---|---|---|
| Intervention | 32 | 61.8 | 10.4 | 1.7 | 0.09 |
| Comparison | 34 | 57.2 | 11.4 | | |

**Table 2:** Independent samples *t*-test for post-test academic achievement scores.

| Group | N | M | SD | *t* | *p*-Value | Cohen's *d* |
|---|---|---|---|---|---|---|
| Intervention | 32 | 79.41 | 7.35 | 3.43 | <0.001 | 0.16 |
| Comparison | 34 | 72.4 | 9.63 | | | |

## 4.2 Qualitative findings

This study employed a reflexive thematic analysis to explore students' lived experiences with virtual laboratories in learning acid-base equilibrium. Interviews with purposively selected students of varying achievement levels revealed rich insights into their perceptions, challenges, and suggestions for improvement. The analysis generated four major themes: experiential engagement and conceptual anchoring, active learning and critical inquiry, skill development and real-world relevance, and challenges related to simulation fidelity, usability, and content breadth.

### 4.2.1 Theme 1: experiential engagement and conceptual anchoring

Students described how virtual laboratories transformed abstract chemical concepts into tangible, visually graspable phenomena. The interactivity enabled them to mentally connect textbook knowledge with dynamic representations, fostering deeper conceptual understanding. T1 (Higher Achiever) shared a detailed reflection:

> *Before using the virtual lab, acid-base equilibrium was something I mostly memorized from textbooks, but I never truly understood what was happening. It was all just formulas and definitions without any real connection to how these reactions look or behave. However, when I started manipulating the acids and bases in the virtual environment, I could actually see the pH changing in real time. I could add acid little by little and observe how the solution's acidity shifted, and that visual and interactive feedback helped me 'see' the chemistry in action. This made the concept less abstract and much more concrete for me. It was like turning invisible chemical processes into something visible and controllable, which made a huge difference in my understanding.*

The phrase *"turning invisible chemical processes into something visible and controllable"* captures the shift from abstract memorization to concrete experience. This underscores how virtual labs act as cognitive tools that embody chemical principles, enhancing mental models essential for science learning.

T3 (Medium Achiever) elaborated on the benefits of visualization for comprehension:

> *I always found buffering and equilibrium concepts quite confusing because they involve invisible ions and shifting balances that I could't picture. The virtual lab allowed me to watch step-by-step how adding acid or base affected the system. Watching the pH meter move and the color change in the simulation gave me a mental image I never had before. It connected the theoretical ideas to something practical and immediate, which made the topic more understandable and less intimidating.*

This reflection illustrates how virtual labs scaffold complex scientific concepts by providing sensory-rich, real-time representations. Such interactive experiences reduce cognitive overload, reinforce understanding, and support conceptual anchoring, enabling learners to bridge the gap between theory and observable phenomena.

### 4.2.2 Theme 2: active learning and critical inquiry

Participants emphasized that virtual laboratories transformed learning into an active process of experimentation, hypothesis testing, and reflection rather than passive reception of information. T2 (Higher Achiever) described this shift in approach:

> *Using the virtual lab was not just about following instructions to complete tasks; it became a process of inquiry. I found myself asking 'What happens if I change this variable?' or 'How will the equilibrium shift if I add more base?' The immediate feedback from the simulation allowed me to test these questions on the spot. Sometimes, the results surprised me and made me rethink what I thought I*

*knew. This process of trial, error, and reflection made me engage with the topic more deeply and critically than just memorizing definitions or reading from a textbook.*

T2's narrative demonstrates how virtual labs promote metacognitive skills and scientific reasoning by encouraging learners to generate hypotheses, test predictions, and revise prior conceptions through immediate experiential feedback.

T5 (Lower Achiever) also emphasized the motivational dimension of active learning:

*The virtual lab was more fun and less frustrating than just reading or listening to lectures. Because I could see instant results from my actions, it kept me interested and willing to try different things. This helped me stay focused and not give up when the topic felt difficult. It made learning feel like a discovery rather than a chore.*

This perspective highlights the affective benefits of interactive environments, where the combination of autonomy and feedback sustains engagement and perseverance. For lower achievers in particular, such design elements transform potentially discouraging content into an exploratory, discovery-driven process. Collectively, these accounts illustrate that virtual labs encourage both cognitive engagement and emotional investment, fostering inquiry, critical reflection, and persistence – key markers of active learning in science education.

#### 4.2.3 Theme 3: skill development and real-world relevance

Beyond strengthening conceptual understanding, students highlighted the role of virtual laboratories in developing essential scientific skills and recognizing the real-world relevance of acid–base equilibrium. T1 reflected on the preparatory value of virtual simulations for hands-on experiments:

*Before I went to the physical chemistry lab, practicing titrations virtually helped me understand the steps and what to expect. It was like rehearsing so that when I handled real equipment, I felt more confident and less nervous. I learned how to set up experiments, measure volumes, and interpret results without the pressure of making mistakes in a real lab. This made me better prepared and improved my practical skills.*

This testimony suggests that virtual labs function as a low-stakes rehearsal environment, enabling learners to acquire procedural fluency, reduce performance anxiety, and transfer skills more effectively into real laboratory contexts. By lowering the fear of error, they support the mastery of technical competencies critical for experimental chemistry. T3 further connected the content to societal impact and community health:

*I once used what I learned about buffer solutions to explain why some local water sources are safer than others. It showed me that chemistry is not just theoretical but affects everyday life and community health. This made me more interested and gave my studies a real purpose.*

This reflects the principles of situated learning, in which abstract knowledge becomes more meaningful when contextualized in real-life scenarios. By linking chemical concepts to environmental and public health issues, virtual labs foster a sense of relevance and responsibility, motivating learners to see science as socially significant.

T6, a lower-achieving student, described the interdisciplinary applications of concepts gained from the virtual lab:

*When I studied soil acidity in biology, I used the pH concepts from the chemistry virtual lab to understand how soil affects plant growth. It helped me see the connections between subjects and how science is interconnected.*

Such insights illustrate how virtual labs encourage integrative scientific thinking, where learners apply chemistry knowledge across subject domains such as biology, agriculture, and environmental studies. This integrative perspective not only strengthens cognitive connections but also prepares students for complex problem-solving in multidisciplinary contexts.

#### 4.2.4 Theme 4: challenges – simulation fidelity, usability, and content breadth

Despite the positive impacts of virtual laboratories, students consistently identified several challenges that constrained their learning experiences. These limitations primarily revolved around simulation fidelity, usability of the platforms, and the breadth of experimental content available. The reflections shared by participants point to the fact that, while virtual laboratories can complement and sometimes enhance traditional teaching, their effectiveness is strongly influenced by the design quality, user interface, and scope of content integration.

#### 4.2.5 Simulation fidelity

Several students expressed concerns regarding the accuracy of the virtual simulations compared to real laboratory experiences. T2 explained:

> *Sometimes, the simulation results don't match exactly what happens in the physical lab – like the color changes or the speed of reactions. This can be confusing because I want to trust what I'm seeing, but when it doesn't align with real experiments, it creates doubt. If virtual labs could incorporate more realistic parameters and match actual lab outcomes better, it would build more confidence in using them as learning tools.*

This concern underscores the importance of fidelity in simulation-based learning environments. When the outcomes of a virtual experiment deviate from what learners expect in a real setting, conceptual confusion may arise. For chemistry education, where color changes, precipitate formation, and reaction rates are critical observable indicators of chemical processes, fidelity directly affects the validity of the learning experience. Prior research also highlights that discrepancies between simulated and actual experiments can reduce learner trust and limit transferability of knowledge to authentic laboratory contexts. Thus, enhancing the realism of simulations is vital to ensure learners perceive virtual laboratories as credible and reliable representations of chemical phenomena.

#### 4.2.6 Usability issues

Another major challenge concerned the interface and navigation of the virtual laboratory platforms. As T5 described:

> *The controls were sometimes hard to figure out, and the instructions weren't always clear. I spent a lot of time just trying to understand how to use the tools, which made it frustrating and slowed my learning down. If the interface was simpler and the instructions clearer, it would help students like me learn more independently and not feel stuck.*

This highlights the critical role of user-centered design in technology-enhanced learning. For many students, especially those who are less technologically proficient, the cognitive effort required to navigate a poorly designed interface competes with the effort needed for conceptual understanding. This aligns with the principles of cognitive load theory, which emphasizes that extraneous load – in this case, struggling with unclear controls – can detract from meaningful learning. A more intuitive interface, supported by step-by-step guidance and scaffolding, could lower these barriers and allow learners to focus more on developing scientific reasoning and problem-solving skills.

#### 4.2.7 Limited experiment variety

Participants also reported limitations in the diversity and scope of experiments available in the virtual laboratory. T3 suggested:

> *While the basic acid-base experiments were well covered, there were few options for more advanced or specialized experiments. I want to explore beyond the basics and try experiments that relate to real-world problems or deeper chemical phenomena. Adding these would make the lab more useful for students who want to push their learning further.*

This perspective draws attention to the need for content differentiation and progressive complexity within virtual laboratory platforms. While introductory experiments provide a solid foundation for learners, advanced students often seek opportunities to extend their knowledge and engage with experiments that simulate real-world challenges or novel research contexts. Without this breadth, virtual laboratories risk being perceived as limited in scope, thereby restricting their capacity to nurture inquiry, creativity, and higher-order thinking skills. Expanding the catalog of experiments would not only broaden student engagement but also allow educators to tailor learning experiences to varied ability levels and curricular goals.

Taken together, these challenges illustrate that the success of virtual laboratories is not determined solely by their availability but also by their design, usability, and curricular relevance. Simulation fidelity ensures that conceptual understanding remains aligned with real-world chemical processes. Usability safeguards learners from unnecessary frustration, supporting smoother engagement. Finally, a broader range of experimental content enables differentiation and sustained learner motivation. Addressing these concerns is essential for optimizing the role of virtual laboratories as powerful tools in secondary chemistry education.

Overall, the qualitative findings reveal that virtual laboratories offer a multifaceted learning experience for students studying acid-base equilibrium. Themes of experiential engagement and conceptual anchoring, active learning and critical inquiry, and skill development and real-world relevance demonstrate that students not only deepen their conceptual understanding but also develop practical laboratory skills and appreciate the broader applicability of chemistry in everyday life. At the same time, challenges related to simulation fidelity, usability, and limited experiment variety highlight areas for improvement to ensure that virtual labs provide accurate, accessible, and sufficiently diverse learning experiences. Collectively, these insights suggest that virtual laboratories can enhance both cognitive and affective dimensions of learning while emphasizing the importance of thoughtful design, realistic simulation, and user-friendly interfaces. By addressing the identified limitations, educators and developers can optimize virtual labs to support meaningful, engaging, and transferable learning outcomes, directly aligning with the study's aim of exploring students' lived experiences and improving instructional strategies in chemistry education.

## 5 Discussion

This mixed-methods study demonstrates the compelling educational value of integrating virtual laboratories into Grade 12 chemistry curricula focused on acid–base equilibrium. Quantitative analysis revealed that students in the experimental group using virtual labs significantly outperformed their peers in the control group on post-test assessments (M = 79.41 vs. 72.4), with a small but meaningful effect size ($d = 0.16$). This result aligns with broader meta-analytic evidence linking immersive technology to improved academic achievement in science.[48]

Pre-test equivalence checks ($t = 1.7$, $p = 0.09$) further support the conclusion that observed learning gains stemmed from the virtual laboratory intervention rather than pre-existing group differences. Concurrent qualitative insights elucidate how and why virtual laboratories facilitate learning. Students consistently described how visual, interactive simulations "made chemistry visible" by enabling observation of pH shifts and equilibrium dynamics in real time – experiences that rendered otherwise invisible chemical processes tangible.[26,41] This observation aligns with dual coding theory and multimedia learning principles, which suggest that combining visual and verbal information enhances comprehension in cognitively demanding domains such as chemistry.[29,30]

Students reported that virtual labs promoted active learning and metacognitive engagement. Rather than merely replicating procedures, students described "testing hypotheses" such as, "what happens if I add more base?" and reflecting in the moment when outcomes were unexpected.[30,50] These findings resonate with contemporary cognitive engagement theories emphasizing learner activity and self-regulation as pathways to achieving learning objectives. Performance improvements correspond closely with these active learning experiences, reinforcing the documented effectiveness of experiential, inquiry-based approaches in science education.[51]

Beyond academic achievement, students highlighted that virtual labs enhanced procedural competence and real-world relevance. Some students reported that virtual titrations prepared them for hands-on experiments, reducing anxiety and improving effectiveness – a result consistent with prior studies demonstrating that well-designed simulations foster procedural fluency and reduce laboratory anxiety.[25,38] Others applied these skills to community-focused tasks, including designing buffer solution protocols for water quality testing and analyzing soil pH in biology projects. Such outcomes are consistent with situated learning theory and reinforce frameworks emphasizing contextualized, applied learning.[52]

Despite these benefits, students identified important limitations. Simulation fidelity emerged as a concern: color changes and reaction timing "didn't always match real lab outcomes," potentially undermining trust and fostering misconceptions.[32] Usability challenges, such as overly complex interfaces and unclear instructions, also impeded progress, particularly among lower-achieving students.[33] These barriers underscore the importance of user-centered design in technology-mediated instruction. Additionally, students noted that many simulations focused on basic experiments without opportunities for advanced exploration. Sustaining engagement and supporting progressive mastery requires tiered content scaffolding, consistent with Vygotsky's zone of proximal development and Bloom's mastery learning principles.[32,53]

Synthesizing these findings, the benefits of virtual laboratories emerge from the interplay between active, visual learning experiences and procedural scaffolding. Learning gains are attributable not solely to the presence of technology but to the intentional design of inquiry-driven, reflective activities embedded within authentic contexts. These pedagogical affordances align with best practices in STEM education, including flipped classroom and problem-based learning models, which emphasize preparation, inquiry, application, and reflection.[54,55]

Practical implications include integrating virtual labs as core instructional tools within flipped or blended learning models, rather than supplementary resources. Educators must design purposeful pre-lab simulations closely linked to in-class inquiry activities. Collaboration between educators and developers is essential to ensure high-fidelity simulations, intuitive interfaces, and comprehensive experiment libraries with graduated complexity. Prioritizing usability and accessibility is critical, especially for learners with limited prior technology experience. Finally, teacher professional development should focus on facilitation strategies, scaffolding, and reflective debriefing to maximize educational impact.[56]

In summary, this study reinforces the educational value of thoughtfully integrated virtual laboratories. Quantitative results indicate measurable learning gains, while qualitative narratives highlight enhanced engagement, skill acquisition, and the application of scientific knowledge. Addressing challenges related to fidelity, usability, and content breadth is critical for sustaining these gains. Future research should explore implementation in other scientific domains, assess longitudinal retention, and examine virtual laboratories' potential in promoting equitable STEM learning across diverse educational contexts.

# 6 Conclusion and recommendations

## 6.1 Conclusions

This study set out to assess the pedagogical effectiveness of virtual laboratories in improving the academic achievement and learning experiences of Grade 12 students studying acid–base equilibrium. Quantitative findings convincingly demonstrated that students exposed to virtual laboratory simulations significantly outperformed their peers who received conventional instruction, affirming the instructional value of digital simulations in science education. The sizable effect size indicates not only statistical but also meaningful practical improvements in student outcomes.

The qualitative component provided critical insight into the mechanisms driving these gains. Students reported that the visual and interactive nature of virtual labs transformed abstract, textbook-based concepts into concrete, manipulable phenomena, fostering deeper conceptual understanding and experiential engagement. The simulations also promoted active learning and critical inquiry by allowing students to hypothesize, experiment, and reflect in a risk-free, motivating environment. Additionally, learners valued the skill development and real-world relevance fostered by the virtual labs, which prepared them for physical laboratory work and demonstrated the practical applications of chemistry in their daily lives.

However, the study also uncovered notable challenges, including discrepancies between simulated and real laboratory outcomes, usability issues with interface designs, and a limited variety of experiments. These shortcomings highlight areas where developers and educators must collaborate to refine the educational design and implementation of virtual laboratories to optimize their effectiveness and accessibility.

Overall, the study's findings contribute meaningfully to the growing body of evidence supporting technology-enhanced instruction in secondary science education, particularly in resource-constrained settings like Ethiopia. It affirms that when thoughtfully integrated, virtual laboratories can serve as powerful pedagogical tools for improving conceptual mastery, fostering scientific inquiry, and enhancing learner motivation.

## 6.2 Recommendations

In light of the findings, several targeted actions are recommended to strengthen the integration and impact of virtual laboratories in secondary school chemistry instruction, particularly in the teaching of acid–base equilibrium.

First, the Ministry of Education (MoE) should take the lead in formulating national guidelines and policy frameworks that formally incorporate virtual laboratories into the secondary science curriculum. This policy should emphasize the use of virtual laboratories to address resource constraints and enhance the teaching of complex scientific concepts.

Furthermore, Regional Education Bureaus and school administrators are urged to allocate adequate financial and technical resources to support the procurement, installation, and maintenance of virtual laboratory software and the necessary ICT infrastructure. They should also facilitate access to these resources for both teachers and students to ensure equity in learning opportunities across schools.

To optimize the instructional use of virtual laboratories, chemistry teachers should receive continuous, practical professional development focused on pedagogical strategies for effectively integrating virtual labs into their lessons. Training should cover not only the technical operation of the software but also innovative methods for fostering inquiry-based, student-centered learning through these platforms.

Moreover, educational technology developers and software designers are advised to enhance the fidelity and instructional design of virtual laboratories. Particular attention should be given to improving the accuracy of simulations, simplifying user interfaces, clarifying instructional prompts, and expanding the variety and complexity of experiments available to accommodate the diverse learning needs of students at different achievement levels.

Finally, curriculum experts and science education researchers should collaborate to design virtual laboratory experiments that are contextually relevant and connected to real-world scientific and environmental problems. This would promote the practical application of classroom knowledge and foster interdisciplinary learning, thereby increasing student engagement, motivation, and retention. These coordinated efforts among policymakers, educators, technology providers, and researchers are essential to realize the full potential of virtual laboratories in transforming science education in Ethiopia.

## 6.3 Limitations and future work

Despite its contributions, this study has several limitations. First, the sample was limited to Grade 12 students from selected schools, which may constrain the generalizability of findings to other grades, regions, or educational contexts. Second, the study focused exclusively on acid–base equilibrium, and the effectiveness of virtual laboratories may differ for other chemistry topics or STEM disciplines. Third, technical limitations – including simulation fidelity, interface usability, and limited experiment variety – may have restricted the intervention's full potential.

Future research should address these limitations by expanding the study to include diverse student populations across multiple grades and regions. Investigating the long-term retention of knowledge and skills acquired through virtual laboratories would provide insight into their sustained impact. Additionally, research exploring virtual lab applications across various chemistry topics and STEM disciplines could inform best practices and guide instructional design improvements. Iterative collaboration between educators, software developers, and curriculum experts is recommended to enhance simulation accuracy, usability, accessibility, and adaptability to diverse learning needs.

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