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Perceptions and challenges in digital chemistry instruction: Student and instructor experiences with virtual laboratories

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Abstract

Virtual laboratories (VLs) provide an effective solution for chemistry education, particularly where limited resources restrict hands-on instruction. This study examined the perceptions and challenges of virtual laboratories among 63 instructors and 143 undergraduate students in universities in Southern Ethiopia. An explanatory sequential mixed-methods design was used. Quantitative data were collected via structured questionnaires and analyzed using descriptive statistics and Cohen's kappa (κ), while qualitative insights were obtained from interviews with 20 instructors. Participants generally agreed on the overall effectiveness of VLs in practical chemistry. They reported that VLs enhance academic performance (mean [M] = 3.8), improve skills development (M = 3.8), and promote flexibility and accessibility (M = 3.9). In interviews, instructors highlighted their usefulness in visualizing abstract concepts, such as molecular interactions. Reported challenges included limited technical skills (κ = 0.63), high software costs (κ = 0.61), weak conceptual clarity to perform VL (κ = 0.61), and lack of engaging software in available computers (κ = 0.51). Recommendations include improving infrastructure, providing training, and integrating hybrid laboratory approaches.

Keywords: perception, challenges, virtual laboratories, practices, chemistry education, descriptive survey, academic performance, technical expertise

INTRODUCTION

Laboratory instruction is a cornerstone of chemistry education, providing students with essential hands-on experience, fostering critical thinking, and bridging the gap between theory and practice (Hofstein, 2004; Reid & Shah, 2007). However, in low-income countries such as Ethiopia, effective laboratory teaching is often hindered by limited financial and material resources, safety concerns, and logistical constraints (Tatli & Ayas, 2013; Tesfamariam et al., 2014). As a result, students receive minimal exposure to practical experimentation, which diminishes their interest in chemistry, undermines their ability to teach the subject effectively, and restricts their employability in industries requiring laboratory skills.

With the growing availability of digital technologies, new opportunities have emerged to enhance science education, especially in resource-constrained settings. One such innovation is the virtual laboratory (VL)–a digital tool that simulates real-world laboratory experiments in a safe, flexible, and cost-effective environment (Kolil et al., 2020). Research indicates that integrating VLs into chemistry instruction can improve students' conceptual understanding, strengthen scientific reasoning skills, and enhance academic performance (Altalbe, 2019; Bazie et al., 2024; Castro, 2025). Although several studies have shown that VLs offer numerous benefits in educational settings, there is limited research on their use in Ethiopian universities, particularly those located in the southern region.

Despite their recognized advantages, the adoption of VLs in universities across many low-income countries remains limited. Key obstacles include inadequate digital infrastructure, the high cost of simulation software, limited technical expertise among faculty, and unstable internet connectivity (Alemseged, 2021; Ngoyi, 2013). In Ethiopia, the *education development roadmap (2018-2030)* emphasizes the integration of information

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Contribution to the literature

- This study provides new empirical evidence on the perceptions and challenges of VL use in chemistry education within Ethiopian universities–an underrepresented context in current research. It combines quantitative survey data with in-depth thematic analysis of instructor interviews to offer a nuanced understanding of both technical and pedagogical barriers to VL implementation.
- It synthesizes existing research on digital instruction and VLs, highlighting key benefits such as enhanced conceptual understanding, development of practical skills, and improved student engagement. It identifies major challenges reported in prior studies, including limited infrastructure, low digital literacy, and high software costs.
- It offers actionable insights for curriculum developers, university policymakers, and national education authorities in low-income settings. It highlights the research gap in under-resourced contexts such as Ethiopian universities, justifying the need for context-specific investigations and guiding future mixed-methods studies.

and communication technologies into the education system. However, implementation at the tertiary level has been uneven and inconsistent, with universities continuing to face significant resources and capacity constraints (Tadesse, 2015; Yigezu, 2021).

In some cases, instructors and students have begun using digital tools–such as simulations and instructional videos–particularly when physical laboratories are unavailable. However, there remains a lack of empirical data regarding how these tools are perceived and experienced within higher education chemistry instruction in Ethiopia. This study seeks to fill this gap by exploring the perceptions, experiences, and challenges faced by both instructors and students in using VLs at selected Ethiopian universities.

By identifying the perceived benefits and barriers to VL implementation, this research contributes to the local understanding of digital chemistry instruction and offers insights that may be applicable to similar educational contexts in other low-resource countries. The findings are expected to inform institutional and national strategies for integrating VLs into chemistry curricula, thereby supporting the broader goals of information and communication technologies -enhanced education outlined in Ethiopia's national policy framework.

Research Aim and Question

Research aim

This study aims to examine instructors' and students' perceptions of the benefits of VLs in chemistry education and to identify the key challenges affecting the implementation and development of virtual chemistry laboratories at universities at Southern Ethiopia.

Research questions

1. How do instructors and students perceive the advantages of integrating VLs into chemistry education?
2. What major barriers hinder the adoption and advancement of virtual chemistry laboratories in universities in Southern Ethiopia?

LITERATURE REVIEW

Digital Instruction in Higher Education

Digital instruction refers to the use of technology to deliver, support, and enhance teaching and learning. It encompasses a range of tools and practices, including learning management systems, instructional videos, simulation software, virtual reality (VR), online assessments, and collaborative platforms (Selwyn, 2016). In higher education, digital instruction has gained prominence due to its potential to increase accessibility, personalize learning, and promote student-centered pedagogies (Anderson, 2008). Recent global shifts–particularly following the COVID-19 pandemic–have accelerated the adoption of digital instruction, making it a central component of education reform in many countries (Hodges et al., 2020). In developing contexts like Ethiopia, digital instruction is recognized in national policies such as the education sector development program and the Ethiopian *education development roadmap (2018-2030)*. However, actual implementation remains limited due to technological, institutional, and human resource barriers (Tadesse, 2015).

Definition of VL

VLs are computer-based environments that simulate real-world scientific experiments, enabling students to perform procedures in a safe, controlled, and interactive setting (De Jong et al., 2013). These platforms can range from two-dimensional desktop simulations to immersive three-dimensional VR environments, providing flexible and engaging learning experiences (Sellberg et al., 2024). VLs often incorporate interactive elements, real-time feedback, and data analysis tools to promote inquiry-based learning and experimentation without physical risks (Klami et al., 2024). Their asynchronous accessibility allows students to explore independently or collaborate with peers at their own pace, making them particularly valuable in contexts where physical laboratory infrastructure is limited (Zhang et al., 2022). By bridging the gap in hands-on experience, VLs serve as essential educational tools that foster practical skills and enhance student engagement (Alexiou et al., 2005; Kashaka, 2024).

Benefits of VLS in Science Education

VLs enhanced science education by bridging the gap between theoretical instruction and simulated practical experience. They provide interactive, inquiry-based, and cost-effective alternatives to traditional laboratories, facilitating student-centered learning across flexible timeframes and geographical locations (Kashaka, 2024). Unlike conventional labs, which often follow rigid experimental procedures, VLs promote exploratory, trial-and-error learning, thereby fostering greater student autonomy, engagement, and critical thinking (More et al., 2024). Empirical studies have shown that VLs can improve students' conceptual understanding, confidence, and knowledge retention. For example, the use of simulations has been linked to enhanced academic performance, increased motivation, and the development of practical skills–outcomes aligned with key benchmarks in higher education quality frameworks (Coleman & Smith, 2019). Although VLs have demonstrated potential in enhancing student engagement and academic performance in science education, most studies on their benefits have been conducted outside Ethiopia, with limited research specifically focused on Ethiopian universities.

Challenges in Implementing VLs in Science Education

Despite their advantages, the implementation of VLs faces several barriers, particularly in resource-constrained settings. Challenges include inadequate information and communications technology (ICT) infrastructure, unreliable internet connectivity, power outages, and a shortage of high-performing computers (Alemseged, 2021; Jafar et al., 2022). Educators and students often lack sufficient training and digital literacy, further hindering effective use (Ngoyi, 2013). Moreover, large student populations, time-consuming software installation processes, and frequent technological updates create additional logistical burdens (Hamed & Aljanazrah, 2020; Kisanga & Ireson, 2015). These challenges call for sustained investments in infrastructure, staff development, and institutional policy support to ensure effective VL integration (Alshurman et al., 2021). However, there is a lack of empirical evidence on how these challenges affect the implementation and effectiveness of VLs in under-resourced settings such as universities in Southern Ethiopia.

Effectiveness of VLs on Academic Achievement

A growing body of research supports the effectiveness of VLs in improving academic performance and practical skills. For instance, one study showed that VLS significantly enhanced conceptual understanding and process skills among hearing-impaired students in electronics experiments (Baladoh et al., 2017). Similarly, virtual chemistry laboratories have been found comparable to real labs in fostering familiarity with laboratory equipment and concepts, though differences in reasoning skills were minimal (Tatli & Ayas, 2013). Other studies report that virtual simulations improve learners' practical skills and perceptions of science learning (Carrasco et al., 2025), with some findings suggesting gender-based differences in effectiveness, particularly favoring male students (Oser, 2013). Overall, these findings indicate that VLs can be powerful tools for enhancing learning outcomes, especially where access to physical labs is limited.

THEORETICAL FRAMEWORK

This study adopts a multidimensional theoretical framework to examine the adoption and effectiveness of VLs in chemistry education within low-resource settings such as Southern Ethiopia. It is anchored in constructivist learning theory, which emphasizes active engagement and knowledge construction through simulated experimentation (AlMulla & Ali, 2023; Oliver 2000). Vygotsky's social development theory complements this by highlighting the role of collaboration and guided interaction in digital learning environments (Cherry, 2021). The technology acceptance model continues to serve as a robust theoretical framework for explaining the adoption of VLs. In particular, it highlights how constructs such as perceived ease of use and perceived usefulness shape behavioral intentions, even in contexts where infrastructural limitations–such as restricted ICT resources or connectivity challenges–may undermine direct usability perceptions (Al-Adwan et al., 2023). To ensure instructional efficiency, cognitive load theory stresses managing mental effort during learning (Sweller, 1988). Self-determination theory further accounts for learner motivation, showing how VLs support autonomy, competence, and relatedness (Ryan & Deci, 2000). Finally, socio-technical systems theory provides a holistic lens on how human, technological, and organizational factors interact to shape the success of educational technologies (Baxter & Sommerville, 2011; Trist, 1981). Collectively, these theories guide the study in assessing both the pedagogical value and implementation challenges of VLs in chemistry education, while underscoring chemistry's foundational role in health-related disciplines.

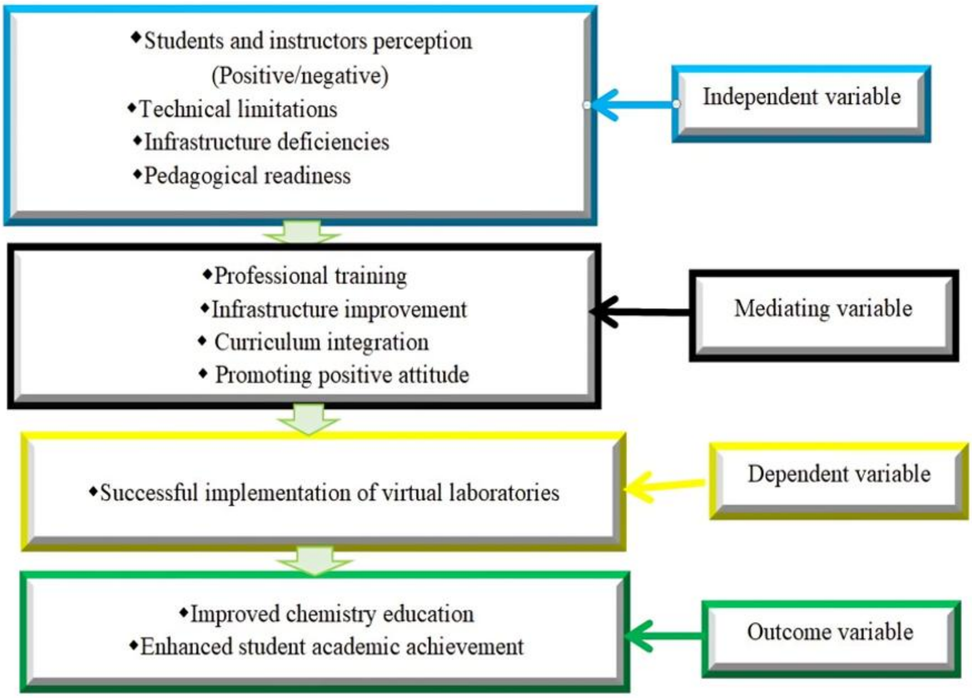

Figure 1. Conceptual framework of the study (Source: Authors' own elaboration)

CONCEPTUAL FRAMEWORK

Figure 1 illustrates the conceptual framework guiding this study, which identifies the key factors influencing the successful implementation of VLs in chemistry education within low-resource university settings. The framework begins with a set of independent variables, including instructors' and students' perceptions (positive or negative), technical limitations, infrastructure deficiencies, and pedagogical readiness. These factors shape a series of mediating institutional responses, such as professional training, infrastructure improvement, curriculum integration, and efforts to promote positive attitudes toward VLs.

When these mediating conditions are effectively addressed, they facilitate the dependent variable–the successful implementation of VLs. This, in turn, leads to the outcome variables: improved chemistry education and enhanced student academic achievement. The framework emphasizes that overcoming technical and pedagogical barriers, while fostering supportive institutional conditions and positive user perceptions, is essential for the sustainable adoption of VLs in higher education.

METHODOLOGY

Research Design

We employed an explanatory sequential mixed-methods design (QUAN→qual), as suggested by Creswell and Plano Clark (2018) to investigate the perceptions and challenges related to VLs in undergraduate chemistry education in Southern Ethiopia.

This design was chosen for its strength in combining quantitative breadth with qualitative depth–first capturing broad patterns through survey data, then interpreting them through in-depth participant narratives. As illustrated in Figure 2, the research began with a quantitative phase involving structured questionnaires administered to chemistry instructors and students who had prior experience with laboratory-based learning. This phase aimed at assessing their perceptions of VLs, highlighting both benefits and challenges. Descriptive statistics were used to identify key trends.

Building on these findings, a purposively selected subset of survey participants was invited to participate in semi-structured interviews. This qualitative phase offered deeper insights into the contextual and institutional factors influencing VL implementation. Data from these interviews were analyzed thematically to capture the complexity of participants' experiences and perspectives.

By sequentially integrating quantitative and qualitative results, this approach provided a comprehensive understanding of the barriers to effective VL instruction. It also enabled the formulation of evidence-based recommendations to improve practical chemistry education in resource-limited university environments.

Participants and Sample

This study involved undergraduate chemistry students and instructors from three Ethiopian universities: Arba Minch University, Wolaita Sodo University, and Dilla University. These institutions were

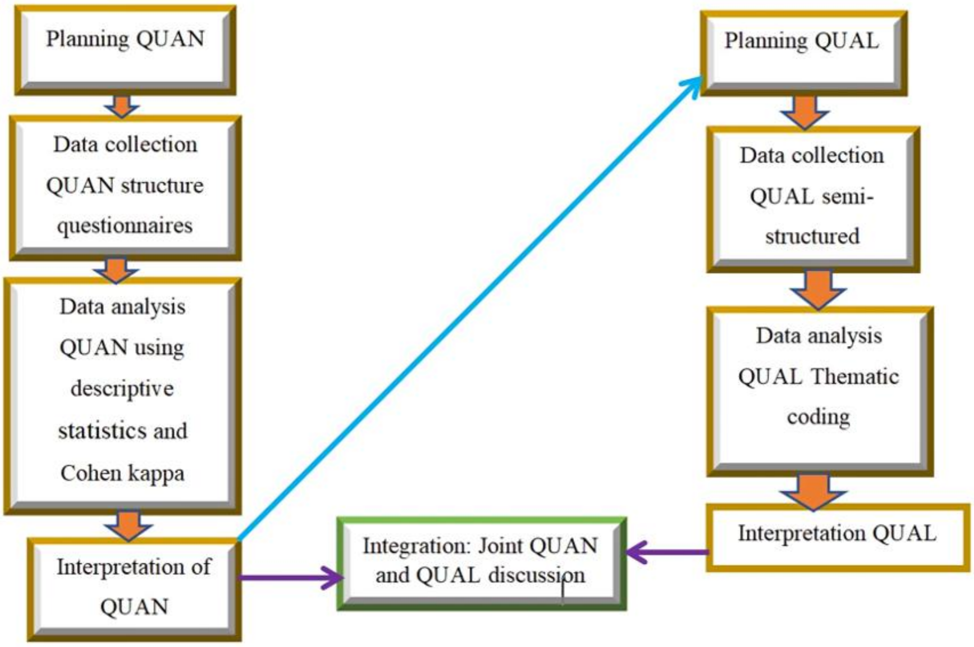

Figure 2. Research design of the study (Source: Authors' own elaboration)

Table 1. Summary of total population and sample size of each university

Institution	Target population			Sample size		
	Chemistry instructors (N)	Undergraduate chemistry students (N)	Total population (N)	Chemistry instructors (n, %)	Undergraduate chemistry students (n, %)	Total sample (n, %)
Dilla university	35	60	95	17 (49.0%)	57 (95.0%)	74 (77.9%)
Wolaita Sodo University	36	59	95	18 (50.0%)	56 (94.0%)	74 (77.9%)
Arba Minch University	60	75	135	30 (50.0%)	71 (95.0%)	101 (75.0%)
Total	131	194	325	65 (50.0%)	184 (95.0%)	249 (77.0%)

purposefully selected to reflect diverse settings in the Southern region and to provide a representative understanding of chemistry education within resource-constrained environments.

Sampling was designed to ensure representativeness and methodological rigor. For chemistry instructors, simple random sampling was employed due to the relatively small and homogeneous population. Based on Cochran's (1977) and Delice's (2010) recommendations, 50% of the instructors from each university were selected to maximize variability. Systematic sampling was applied to reduce potential selection bias, resulting in a sample of 17 instructors from Dilla University, 18 from Wolaita Sodo University, and 30 from Arba Minch University.

For undergraduate students, a stratified sampling technique was used based on academic year (second to fourth year) to ensure proportional representation across cohorts and gender. The total sample size of 184 students was determined using the Krejcie and Morgan formula (Eq. [1]), assuming a 95% confidence level, a 5% margin of error, and a population proportion of 0.5 to maximize sample variability (Chua, 2006). Within each stratum, systematic sampling was used to select participants proportionally, yielding 57 students from Dilla University, 56 from Wolaita Sodo University, and 71 from Arba Minch University. **Table 1** presented summary of target population and participants

$$n = \frac{X^2NP(1-P)}{d^2(N-1)+X^2p(1-p)}, \tag{1}$$

where n is sample size, X^2 is the Chi-square value for the desired confidence level (3.841), N is the total population size, P is population proportion (50% or 0.5), and d is degree of accuracy (0.05).

Eligibility criteria required that instructors have at least three years of experience teaching laboratory-based chemistry courses. Students were eligible if they were in their second to fourth year and had completed at least one laboratory-based chemistry course. Participation was voluntary, and informed consent was obtained from all participants. Individuals without relevant experience or who declined to participate were excluded from the study.

Data Collection Instrument

To comprehensively investigate perceptions and challenges related to virtual chemistry laboratories, this study employed a mixed-methods approach using both structured questionnaires and semi-structured interviews. The questionnaire consisted of 29 items across three sections:

(1) demographic information (e.g., age, gender, academic qualification, and teaching experience),

(2) perceptions of VLs (effectiveness, usefulness, and satisfaction), and

(3) implementation challenges (technical, infrastructural, and institutional barriers).

Items were adapted from validated instruments used in prior research (Barak & Dori, 2005; Makransky et al., 2016; Smetana & Bell, 2012; Tatli & Ayas, 2013) and were modified to fit the Ethiopian higher education context. Responses were recorded on a 5-point Likert scale ranging from "strongly disagree" to "strongly agree." Content validity was ensured through expert review, and a pilot test involving 40 participants helped improve clarity and reliability. To complement the quantitative data, semi-structured interviews were conducted with 5-10 purposively selected instructors from each university, ensuring diversity in gender, teaching experience, and academic background. A consistent set of open-ended questions guided the interviews, allowing for both comparability and flexibility. These interviews provided deeper qualitative insights into participants' experiences, attitudes, and recommendations, enriching the overall understanding of VL integration.

Validity and Reliability Test of the Research Instruments

To assess perceptions of the benefits and challenges of VLs, the study developed two initial sets of questionnaire items–18 items related to perceived benefits and 18 items addressing implementation challenges–based on established literature in virtual science education (e.g., Makransky et al., 2016; Smetana & Bell, 2012; Tatli & Ayas, 2013).

Validity assessment

Content and construct validity were examined by three psychology and science education experts to ensure conceptual clarity and alignment with the study's objectives. Based on expert feedback, seven items (four from the benefits scale and three from the challenges scale) were eliminated, while others were revised or reorganized to enhance clarity, reduce redundancy, and ensure contextual relevance. These modifications significantly improved the face and content validity of the instrument.

Reliability assessment

A pilot test was conducted at Kotebe University of Education involving 10 chemistry instructors and 30 upper-year undergraduate chemistry students. Internal consistency was measured using Cronbach's alpha, which yielded values of 0.839 for the perceived benefits scale and 0.849 for the implementation challenges scale. According to Taber (2018), alpha values between 0.8 and 0.9 indicate good reliability, confirming that the instruments were statistically sound and suitable for use in the main study.

Table 2. Interpretation of Kappa test result

Kappa value	Interpretation
$\kappa < 0$	Less than chance agreement
$0 \leq \kappa \leq 0.20$	Poor agreement
$0.21 \leq \kappa \leq 0.40$	Fair agreement
$0.41 \leq \kappa \leq 0.60$	Moderate agreement
$061 \leq \kappa \leq 0.80$	Substantial agreement
$0.81 \leq \kappa \leq 1.00$	Almost perfect agreement

Data Analysis Tools and Techniques

This study employed both quantitative and qualitative data analysis methods to comprehensively address the research objectives.

Quantitative analysis

Descriptive statistics–such as means, frequencies, and percentages–were used to summarize responses gathered using a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). For interpretation, the interval classification method proposed by Boone and Boone (2012) and Alkharusi (2022) was applied:

- 1.00-1.80 = strongly disagree
- 1.81-2.60 = disagree
- 2.61-3.40 = neutral
- 3.41-4.20 = agree
- 4.21-5.00 = strongly agree

To enhance interpretability, mean values were arranged in ascending order. Average scores for each item were calculated by combining the responses of instructors and students. When the group means were close or identical, a combined average was reported. However, in cases of noticeable variation, group means were analyzed separately to capture differing perspectives (Creswell, 2014). Items with a mean score of 3.6 or higher, as reported by both instructors and students, were considered to reflect a positive perception and were included in the findings

In addition, the kappa statistics were employed to assess the level of agreement between students and instructors regarding the challenges of implementing VLs. Unlike simple percentage comparisons, the kappa coefficient accounts for agreement occurring by chance. As shown in **Table 2**, kappa values range from -1 (complete disagreement) to +1 (perfect agreement), with 0 indicating no better agreement than would be expected by chance (McHugh, 2012). The kappa test was applied only to items where 50% or more of respondents in both groups either agreed or disagreed, ensuring reliable interpretation despite the unequal sample sizes (N = 63

Table 3. Timeline of the study

Activity	Description	Date (day/month/year)
Proposal approved	Approval of the research proposal	30 June 2023
Preparation of questionnaires	Development and finalization of questionnaires	1 July 2023-20 September 2023
Pilot test	Conducted a pilot test to refine the questionnaires	16 October 2023
Distribution of questionnaires	Dispatched questionnaires to respondents	20 December 2023
Data collection	Collection of returned questionnaires	1 January 2024-29 February 2024
Questionnaires data analysis	Analyzed the data collected through questionnaires	1 March 2024-25 April 2024
Conducting interviews	Conducted interviews with participants	12 May 2024-20 May 2024
Interview data analysis	Analyzed the collected data through interview	12 June 2024-8 July 2024
Integrated the data analyzed	Integrate the data analyzed through both interviews and questionnaires	15 July 2024-31 August 2024
Writing the research	Compiled and wrote the research findings	3 September 2024-30 December 2024
Submission to journal	The manuscript was written, suitable journals were identified, and the paper was submitted for consideration	Starting 1 February 2025

Table 4. Response rate

Respondents	Sample size (N)	Returned questionnaires (n)	Returned rate (%)
Instructors	65	63	96.9
Students	184	143	77.7
Total	249	206	86.3

and N = 143). Items not meeting this threshold were analyzed qualitatively to explore divergent perspectives. Items that received moderate to perfect agreement levels (Cohen's kappa values between 0.41 and 1.00), and where both instructors and students expressed agreement, were identified as significant barriers to the implementation of virtual chemistry laboratories.

Qualitative analysis

A thematic analysis was conducted on interview transcripts to extract in-depth insights. Responses were coded to identify recurring patterns and grouped into broader thematic categories related to VL experiences. Themes were iteratively refined for coherence and accuracy, and both converging and diverging viewpoints were examined. To enhance the richness and authenticity of the qualitative findings, direct participant quotes were used to illustrate key points.

Study Timeline

The study followed a structured timeline to ensure systematic implementation of all research activities(**Table 3**). The research proposal was approved on June 30, 2023, after which the preparation and finalization of questionnaires were conducted from July 1 to September 20, 2023. A pilot test was carried out on October 16, 2023, to refine the questionnaires. The finalized questionnaires were distributed to respondents on December 20, 2023, and data collection from the returned questionnaires occurred between January 1 and February 29, 2024, followed by analysis of the questionnaire data from March 1 to April 25, 2024.

Interviews with selected participants were conducted from May 12 to May 20, 2024, and the resulting interview data were analyzed between June 12 and July 8, 2024. The integration of both questionnaire and interview data took place from July 15 to August 31, 2024, after which the research findings were compiled and written between September 3 and December 30, 2024. Finally, the manuscript was prepared, relevant journals were reviewed, and submission was initiated on February 1, 2025.

Ethical Consideration

The study adhered to ethical research principles, including autonomy, beneficence, non-maleficence, and justice. Ethical approval was granted by the Institutional Review Board at Hawassa University (protocol no. CNCS-REC030/23). Informed oral consent was obtained, participation was voluntary, and confidentiality was maintained. The research aimed to enhance chemistry education in resource-limited university settings.

RESULTS

Response Rate

As shown in **Table 4**, the return rate for instructors was 96.9%, demonstrating strong participation, while the students' return rate was 77.7%, indicating substantial involvement. The overall return rate for both groups was 86.3%, exceeding the 70% threshold considered acceptable for analysis (Babbie, 2020). This return rate is deemed adequate for the study's analysis.

Table 5. Respondent's demography profile

No	Item		Chemistry instructors (N = 63)		Undergraduate chemistry students (N = 143)	
			Frequency (n)	Percentage (%)	Frequency (n)	Percentage (%)
1	Gender	Male	58	92.1	124	86.7
		Female	5	7.9	19	13.3
		Total	63	100	143	100
2	Age	21-30	10	15.9		
		31-40	27	42.9		
		41-50	22	34.9		
		> 50	4	6.3		
		18-20			5	3.5
		21-23			128	89.5
		24-27			9	6.3
		28-30			1	0.7
3	Educational status	PhD/DEd	20	31.7		
		MSc/MEd	39	61.9		
		BSc/BEd	4	6.3		
	Academic level	2nd year			11	7.7
		3rd year			40	28.0
		4th year			92	64.3
4	Working experience	< 5	3	4.8		
		6-10	19	30.2		
		11-15	21	33.3		
		16-20	9	14.3		
		> 20	11	17.4		

Respondents Characteristics

The demographic characteristics of the respondents are summarized in Table 5. Among the instructors, the majority were male (92.1%), with females accounting for only 7.9%. Age-wise, 42.9% were in the 31-40 range, 34.9% were 41-50, 15.9% were 21-30, and 6.3% were above 50 years. Regarding qualifications, 61.9% held an MSc/MEd, 31.7% a PhD/DEd, and 6.3% a BSc/BEd.

In terms of teaching experience, 33.3% had 11-15 years, 30.2% had 6-10 years, and 17.4% had over 20 years. Among students, 86.7% were male, and most (89.5%) were between 21-23 years old.

Regarding academic level, 64.3% were 4th year students, 28.0% were 3rd year, and 7.7% were 2nd year.

This demographic profile indicates that the sample largely consists of male respondents, experienced instructors with advanced degrees, and senior students nearing graduation–offering relevant perspectives for this study.

Perceptions of Instructors and Students on the Benefits of VLs

Quantitative insight from instructors and students

Ease of use and conceptual understanding: Table 6 presents participants' attitudes regarding the usability and conceptual clarity of VLs.

For item Atvd1, which stated that "the VL does not assist students in preparing for the next lab session," both instructors and students reported mean scores of mean (M) = 2.3, placing it within the "disagree" range (1.81-2.60). This indicates that most participants believed VLs do support students in preparing for upcoming practical sessions.

For item Atvd2, which stated that learning or teaching practical chemistry through VLs makes concepts difficult to grasp, instructors reported M = 2.4 and students reported M = 2.6. These values also fall within the disagreement range, suggesting that participants generally did not find VLs confusing or difficult in terms of conceptual understanding in chemistry.

Interest and interaction in VL learning: Table 7 presents participants' perceptions of the role of VLs in enhancing learning interest and providing flexible, interactive instruction.

For item Atvn1, which asked whether VLs increase students' interest in learning chemistry, instructors reported a mean score of M = 3.4, placing it at the upper boundary of the neutral range (2.61-3.4). This indicates that instructors held a neutral stance, reflecting uncertainty about the motivational impact of VLs.

Similarly, for item Atvn2, which assessed whether VLs offer greater flexibility and support interactive learning within a shorter timeframe, students reported a mean score of M = 3.4, also within the neutral range. This suggests that students were undecided about the extent to which VLs provide flexible and interactive learning opportunities within limited time.

Table 6. Descriptive statistics on attitudes toward ease of use and understanding of VLs

Items code	Item description	M	Group
$Atvd_1$	The VL does not assist students in preparing for the next lab session.	2.3 2.3	Instructors Students
$Atvd_2$	Teaching or learning practical chemistry courses (experiments) with VL makes it difficult to follow and understand the concept.	2.4 2.6	Instructors Students

Note. Lower M values (closer to 2.0) indicate disagreement, suggesting participants generally found VLs easy to follow and useful for supporting future laboratory preparation

Table 7. Descriptive statistics on perceived interest and flexibility in VL learning

Items code	Item description	M	Group
$Atvn_1$	Using a VL for practical chemistry enhances students' interest in learning chemistry.	3.4	Instructors
$Atvn_2$	VLs offer greater flexibility and interactive learning opportunities in a shorter time.	3.4	Students

Note. M values in the 2.61-3.4 range indicate a neutral level of agreement, suggesting that participants neither strongly endorsed nor rejected the role of VLs in promoting interest and interactive engagement

Table 8. Descriptive statistics on attitude toward the effectiveness of VL learning

Items code	Item description	M	Group
$Atva_1$	Teaching or learning chemistry courses via virtual learning enhances the quality of learning chemistry.	3.9 4.0	Instructors students
$Atva_2$	Teaching or learning practical chemistry courses with a VL increases students' achievement.	3.7 3.9	Instructors students
$Atva_3$	Using a VL in the teaching and learning process enables both instructors and students to improve their understanding and enhance their teaching and learning skills.	3.7 3.9	Instructors students
$Atva_4$	VLs are useful alternatives when conducting real experiments is not possible.	3.9 4.0	Instructors students
$Atva_5$	VLs help students better understand chemistry concepts when real experiments cannot be conducted.	3.8 4.0	Instructors students
$Atva_6$	VLs enhance students' scientific skills in practical chemistry.	3.9 3.9	Instructors students
$Atva_7$	Teaching or learning practical chemistry through VLs allows students to develop their own hypotheses and enhance their problem-solving skills.	3.6 3.8	Instructors students
$Atva_8$	VLs facilitate easier lab report writing by allowing students to repeatedly review experiments.	3.8 3.9	Instructors students
$Atva_9$	VLs enhance students' understanding of complex chemistry concepts in practical courses.	4.0 3.9	Instructors students
$Atva_{10}$	VLs facilitate self-paced learning in practical chemistry courses.	3.9 3.9	Instructors students
$Atva_{11}$	VLs offer instructors and students more instructional options within shorter timeframes while enhancing interaction.	3.8	Instructors
$Atva_{12}$	VLs enhance students' interest in learning chemistry during practical courses.	4.0	Students

Note. Atva1-Atva12 reflects attitudes toward effectiveness of VL learning with higher mean scores indicating an agreement

Effectiveness of VLs in enhancing chemistry teaching and learning: Table 8 presents data on participants' attitudes regarding the effectiveness of VLs in enhancing the quality of chemistry teaching and learning.

The overall mean score for items Atva1 to Atva10 was M = 3.8, which falls within the 3.41-4.20 range, indicating a general level of agreement among both instructors and students. These results suggest that participants view VLs positively, recognizing their contributions to **academic performance**, which includes: enhancing learning quality (Atva1, M = 3.9), improving student achievement (Atva2, M = 3.8), and strengthening conceptual understanding (Atva3, Atva5, Atva9, M = 3.8); **skill development**, which includes promoting problem-solving (Atva7, M = 3.7), facilitating lab report writing (Atva8, M = 3.9), and developing scientific skills (Atva6, M = 3.9); and **flexibility and accessibility**, which includes supporting self-paced learning (Atva10, M = 3.8) and providing alternatives when real laboratories are unavailable (Atva4, M = 3.9).

Learning interest, interaction and engagement: Item Atva11 assessed instructors' perceptions of whether VLs provide more instructional options within a shorter time and enhance interaction (Table 8). The mean score of M = 3.8 falls within the "agree" range (3.41-4.20), indicating that instructors generally view VLs as efficient educational tools that support flexible teaching methods and promote interactive learning environments.

Item Atva12 measured students' perceptions of whether VLs increased their interest and motivation to learn chemistry (**Table 8**). The mean score of M = 4.0, also within the "agree" range (3.41-4.20), suggests that most students perceive VLs as engaging tools that stimulate curiosity and motivation, thereby fostering greater interest in learning chemistry.

Qualitative insights from instructor interviews

In-depth interviews were conducted with chemistry instructors (N = 20) from Arba Minch, Dilla, and Wolaita Sodo universities. A semi-structured interview approach was employed, with the central question being: *"What is your perspective on the use of VLs in chemistry instruction, and how do you see them contributing to students' learning experiences?"* Follow-up questions were used to probe deeper into specific themes that emerged during the interview process.

Theme 1. Essential role of real laboratories for practical skill development: Instructors strongly emphasized that real laboratories remain indispensable for developing students' practical skills. They pointed out that while VLs can illustrate procedures conceptually, they cannot replicate the tactile learning, direct manipulation of apparatus, or real-time problem-solving experiences that are vital for mastering laboratory techniques. As one instructor from Arba Minch University noted:

> "Real labs are irreplaceable, as they offer genuine hands-on experience that VLS cannot fully replicate."

This underscores the belief that authentic skill acquisition in chemistry requires physical engagement with materials and equipment, which virtual simulations alone cannot provide.

Theme 2. VLs as effective complementary tools: Participants consistently described VLs as valuable supplements to real labs rather than replacements. Instructors noted that VLs help students understand theoretical aspects of chemistry more deeply, making them better prepared and more confident during real lab sessions. As explained by a Dilla University instructor:

> "VLs help students grasp core chemistry concepts, facilitating their performance in real lab experiments."

This theme reflects the supportive instructional role VLs play in bridging theory and practice, ultimately enhancing students' readiness for hands-on experimentation.

Theme 3. VLs as practical alternatives in resource-limited contexts: In contexts where access to physical laboratories is restricted–due to equipment shortages, scheduling limitations, or emergency conditions– VLs were widely viewed as practical alternatives that ensure learning continuity. Instructors appreciated the ability of VLs to simulate experiments when real lab sessions were not feasible. As one instructor from Wolaita Sodo University stated:

> "When real experiments are not feasible due to challenges like lack of equipment, VLs serve as a practical alternative to ensure learning continues."

This perspective highlights the strategic utility of VLs in maintaining instructional delivery despite logistical constraints.

Theme 4. Enhancing conceptual understanding through VLs: Several instructors highlighted that VLs are particularly effective in improving students' comprehension of complex and abstract chemistry concepts. Through interactive simulations and visualizations, VLs help make theoretical content more accessible and engaging. In a controlled, risk-free environment, students are able to experiment without fear of hazards or making costly mistakes. As one instructor from Arba Minch University explained:

> "Animations of molecular collisions helped students visualize what they couldn't grasp in textbooks."

This illustrates the pedagogical value of VLs in fostering deeper cognitive engagement.

Theme 5. Support for preparation and review: Instructors also identified VLs as useful tools for both pre-laboratory preparation and post-experiment review. By allowing students to preview laboratory procedures beforehand and revisit completed experiments afterward, VLs help reinforce key concepts and build learner confidence. This dual functionality supports continuous learning beyond scheduled lab sessions. A Wolaita Sodo University instructor emphasized:

> "VLs are useful for preparing students ahead of lab sessions and for reviewing experiments previously conducted in real labs."

These insights show how VLs contribute to more thorough and flexible learning experiences in practical chemistry education.

Challenges to Implement and Develop VLs in Chemistry Education

Challenges related to awareness and perception of VLs (cv1-cv3)

Item Cv1 examined awareness of VLs. While 54% of students viewed lack of awareness as a challenge, only 19% of instructors agreed (**Table 9**). With 73% of instructors disagreeing, the issue was not considered a

Table 9. Descriptive statistics result of challenges with respect to awareness and perception

Items code	Items description	Response type	n (%)		κ
			Instructors	Students	
Cv_1	Chemistry instructors, lab technicians and students are not aware of the existence of a VL.	Strongly agree	2 (3.2)	20 (14.0)	Not applicable
		Agree	11 (17.5)	58 (40.6)	
		Neutral	4 (6.3)	20 (14.0)	
		Disagree	32 (50.8)	30 (21.0)	
		Strongly disagree	14 (22.2)	15 (10.5)	
Cv_2	Assuming that it doesn't matter whether you teach/learn a practical chemistry course using a VL or not because VLs don't replace real laboratories.	Strongly agree	1 (1.6)	15 (10.5)	0.35
		Agree	11 (17.5)	27 (18.9)	
		Neutral	4 (6.3)	16 (11.2)	
		Disagree	29 (46.0)	55 (38.4)	
		Strongly disagree	18 (28.6)	30 (21.0)	
Cv_3	Believing that the idea that teaching/learning practical chemistry through VLs makes it harder to fully understand the concepts.	Strongly agree	4 (6.3)	6 (4.2)	0.47
		Agree	10 (15.9)	23 (16.1)	
		Neutral	7 (11.1)	27 (18.9)	
		Disagree	35 (55.6)	59 (41.3)	
		Strongly disagree	7 (11.1)	28 (19.6)	

Table 10. Descriptive statistics result of challenges with respect to technical challenges

Items code	Items description	Response type	n (%)		κ
			Instructors	Students	
Cv_4	Not knowing how to teach/learn using virtual chemistry lab.	Strongly agree	1 (1.6)	14 (9.8)	Not applicable
		Agree	8 (12.6)	63 (44.1)	
		Neutral	4 (6.3)	35 (24.5)	
		Disagree	37 (58.7)	22 (15.4)	
		Strongly disagree	13 (20.6)	9 (6.7)	
Cv_5	The lack of understanding of certain concepts to perform experiments using a virtual chemistry laboratory.	Strongly agree	12 (19.04)	40 (28)	0.61
		Agree	31 (49.2)	78 (54.5)	
		Neutral	3 (11.1)	10 (6.9)	
		Disagree	10 (15.9)	11 (7.7)	
		Strongly disagree	7 (11.1)	4 (2.8)	
Cv_6	Instructors and students lack technical expertise to operate VL software effectively.	Strongly agree	5 (7.9)	26 (18.2)	0.63
		Agree	45 (71.4)	85 (59.4)	
		Neutral	3 (4.8)	10 (6.9)	
		Disagree	8 (12.6)	12 (8.4)	
		Strongly disagree	2 (3.2)	10 (7.0)	

major barrier by faculty. As agreement in both groups was below 50%, Cohen's kappa (κ) was not computed.

Item Cv2 assessed whether VLs are seen as unnecessary substitutes for real labs. Most instructors (74.6%) and students (59.4%) disagreed, reflecting a shared view of VLs as complementary tools. The level of agreement was fair (κ = 0.35).

Item Cv3 examined whether VLs hinder conceptual understanding. Most instructors (66.7%) and students (60.9%) disagreed, indicating that VLs aid rather than obstruct learning. The agreement between groups was moderate (κ = 0.47).

Technical barriers to effective use of VLs (Cv4-Cv6)

Item Cv4 assessed knowledge barriers in using VLs (**Table 10**). While 79% of instructors disagreed that lack of knowledge was an issue, 54% of students viewed it as a challenge. Due to this disparity, κ was not computed.

Item Cv5 examined difficulties in understanding concepts necessary for conducting virtual experiments. A majority of instructors (68%) and students (82.5%) agreed this was a challenge. Agreement was substantial (κ = 0.61), reflecting shared recognition of the cognitive demands associated with VL use.

Item Cv6 assessed technical expertise. Most instructors (79%) and students (77.6%) identified this as a key barrier. Agreement was substantial (κ = 0.63), indicating that both groups recognized limitations related to technical skills.

Resource constraints in virtual chemistry lab implementation (Cv7-Cv9)

Item Cv7 focused on financial limitations (**Table 11**). A majority of instructors (68%) and students (61%) agreed that the high cost of software development and acquisition poses a significant barrier. Agreement was substantial (κ = 0.61), highlighting cost as a shared concern.

Table 11. Descriptive statistics result of challenges with respect to technical challenges

Items code	Items description	Response type	n (%)		κ
			Instructors	Students	
Cv_7	The high cost of developing and acquiring VL software is a significant barrier for institutions.	Strongly agree	10 (15.9)	22 (15.4)	0.61
		Agree	33 (52.4)	65 (45.5)	
		Neutral	11 (17.5)	36 (25.2)	
		Disagree	6 (9.5)	11 (7.7)	
		Strongly disagree	3 (4.8)	9 (6.3)	
Cv_8	Instructors do not know the sources of VL.	Strongly agree	3 (4.8)	27 (18.9)	Not applicable
		Agree	21 (33.3)	31 (21.7)	
		Neutral	10 (15.9)	46 (32.1)	
		Disagree	25 (39.7)	27 (18.9)	
		Strongly disagree	4 (6.3)	12 (8.4)	
Cv_9	Lack of interesting software in a set of computer programs.	Strongly agree	10 (15.9)	32 (22.4)	0.51
		Agree	39 (61.9)	59 (41.3)	
		Neutral	7 (11.1)	32 (22.4)	
		Disagree	5 (7.9)	12 (8.4)	
		Strongly disagree	2 (3.2)	8 (5.6)	

Table 12. Descriptive statistics result of challenges with respect to technical challenges

Items code	Items description	Response type	n (%)		κ
			Instructors	Students	
Cv_{10}	Instructors are not ready to use VLs to overcome problems associated with real lab experiments.	Strongly agree	9 (14.28)	19 (13.3)	0.37
		Agree	29 (46.0)	63 (44.1)	
		Neutral	4 (6.3)	34 (23.8)	
		Disagree	14 (22.2)	22 (15.4)	
		Strongly disagree	7 (11.1)	5 (3.5)	
Cv_{11}	Stakeholders are not motivated to use VL.	Strongly agree	7 (11.1)	19 (13.3)	Not applicable
		Agree	23 (36.5)	37 (25.9)	
		Neutral	8 (12.7)	48 (33.5)	
		Disagree	20 (31.7)	27 (18.9)	
		Strongly disagree	4 (6.3)	12 (8.4)	

Item Cv8 assessed awareness of available VLs resources. Responses were split, with 38% of instructors and 40% of students acknowledging this as a challenge. Due to the low agreement, κ was not computed.

Item Cv9 explored the lack of engaging software. Most instructors (78%) and students (64%) identified this as a problem. Agreement was moderate (κ = 0.51), indicating a common concern regarding the limited interactivity of existing VL tools.

Motivation and readiness (Cv10 & Cv11)

Item Cv10 examined instructors' readiness to adopt VLs as alternatives to real-lab challenges (**Table 12**). Agreement was noted among 60% of instructors and 57% of students, while 36.4% of instructors disagreed. Agreement was fair (κ = 0.37), suggesting partial alignment but notable differences in perception.

Item Cv11 focused on motivation to use VLs. Agreement on lack of motivation was relatively low–47.6% among instructors and 39.2% among students–with many respondents remaining neutral. Due to dispersed responses, κ was not computed.

Infrastructure and research gap (Cv12-Cv15)

Item Cv12 assessed whether VLs are perceived as unnecessary in institutions with well-equipped real labs (**Table 13**). A majority of instructors (72%) and students (61%) disagreed, affirming the relevance of VLs even in such settings. Agreement was moderate (κ = 0.47).

Item Cv13 addressed internet connectivity as a barrier. Agreement was observed among 38% of instructors and 41% of students, while 46% of instructors disagreed and 37% of students remained neutral. Due to the dispersed responses, κ was not computed.

Item Cv14 explored the availability of computer laboratories. A majority of instructors (54%) and students (58%) agreed that their departments lack the infrastructure to support VLs. Agreement was fair (κ = 0.25).

Item Cv15 examined the perceived lack of local research on VLs. Agreement was observed among 52% of instructors and 44% of students, while others were neutral or disagreed. Due to the mixed responses, κ was not calculated.

Table 13. Descriptive statistics result of challenges with respect to infrastructure and research gap

Items code	Items description	Response type	n (%)		κ
			Instructors	Students	
Cv_{12}	No need of using a VL since there are well equipped chemistry laboratories.	Strongly agree	1 (1.6)	18 (12.6)	0.50
		Agree	7 (11.1)	26 (18.2)	
		Neutral	1 (1.6)	12 (8.4)	
		Disagree	30 (47.6)	42 (29.4)	
		Strongly disagree	24 (38.1)	45 (31.5)	
Cv_{13}	Poor university Internet connectivity hinders the use of computer-based laboratories.	Strongly agree	3 (4.8)	27 (18.9)	Not applicable
		Agree	21 (33.3)	31 (21.7)	
		Neutral	10 (15.9)	46 (32.1)	
		Disagree	25 (39.7)	27 (18.9)	
		Strongly disagree	4 (6.3)	12 (8.4)	
Cv_{14}	The department or college lacks a dedicated computer lab for conducting virtual experiments.	Strongly agree	12 (19.0)	44 (30.0)	0.25
		Agree	22 (34.9)	40 (28.0)	
		Neutral	8 (12.7)	16 (11.2)	
		Disagree	20 (31.7)	29 (20.3)	
		Strongly disagree	1 (1.6)	14 (9.8)	
Cv_{15}	The lack of research on VLs in Ethiopia makes their impact on student achievement unclear.	Strongly agree	7 (11.1)	16 (11.2)	Not applicable
		Agree	26 (41.3)	47 (32.9)	
		Neutral	17 (27.0)	24 (16.8)	
		Disagree	10 (15.9)	36 (25.2)	
		Strongly disagree	3 (4.6)	20 (14.0)	

DISCUSSION

This study explored the perceptions of instructors and students, as well as the challenges associated with implementing VLs in chemistry education at three universities in Southern Ethiopia. Items with a mean score of 3.6 or higher, as reported by both instructors and students, were interpreted as reflecting a positive perception and were included in the findings. Similarly, items that demonstrated moderate to perfect agreement (κ values between 0.41 and 1.00) and where both groups expressed agreement were identified as key barriers to the successful implementation of virtual chemistry laboratories

Perceptions of Instructors and Students on the Benefits of VLs

The findings indicate that instructors and students recognized multiple advantages of VLs particularly in enhancing academic performance through improvements in learning quality, student achievement, and conceptual understanding (M = 3.8). They also supported skill development, including problem-solving, lab report writing, and scientific skills (M = 3.8). Flexibility and accessibility were additional strengths, enabling self-paced learning and providing alternatives when physical laboratories were unavailable (M = 3.9). These results suggest that VLs reinforce theoretical knowledge while fostering essential practical competencies, serving as a valuable complement to traditional laboratory instruction. Qualitative data further highlighted their role in preparing students for real laboratory work, although hands-on skills cannot be fully developed through simulations alone. Overall, VLs are most effective as complementary tools, particularly in resource-constrained settings. Successful implementation requires reliable, user-friendly platforms, adequate instructional support, and targeted instructor training. Policymakers and academic administrators are encouraged to adopt hybrid approaches that integrate VLs and physical laboratories to maximize learning outcomes.

These findings align with previous research underscoring the effectiveness of VLs in chemistry education. For instance, Rosli et al. (2022), Lamb (2020), and Bazie et al. (2024) found that VLs significantly improve students' conceptual understanding, academic performance, and scientific process skills. The positive perceptions identified in this study further support the notion that VLs can mitigate resource limitations, foster autonomous learning, and promote essential scientific competencies–ultimately contributing to improved educational quality. In line with this, Miyamoto et al. (2019) emphasized that VLs can help develop practical skills and reinforce experimental procedures, while Abdelmoneim (2022) found that simulation-based tools enhance scientific knowledge, decision-making, and higher-order thinking. Similarly, Hamed and Aljanazrah (2020) reported that students exposed to VLs environments showed deeper understanding and greater preparedness for real lab work.

Challenges to Implementing and Developing VLs in Chemistry Education

Despite their educational benefits, this study identified several challenges hindering the effective implementation of VLs in chemistry education. One major barrier was a limited understanding among both instructors and students regarding the pedagogical relevance and operational use of VLs. This was supported by a substantial level of inter-rater agreement (κ = 0.61), indicating a shared unfamiliarity with VL concepts. These findings highlight the need for structured orientation and training programs to facilitate the effective adoption of virtual technologies. Another significant obstacle was the lack of technical skills, as reflected in reports of low digital proficiency by both groups (κ = 0.63). This underscores the importance of targeted professional development initiatives aimed at improving digital literacy among instructors and students. Furthermore, participants frequently cited resource-related issues, including the high cost of acquiring or developing VLs software and dissatisfaction with the lack of engaging or interactive content (κ = 0.61 and 0.51, respectively). Without adequate funding and support, the potential of VLs to transform science education may remain unrealized. Therefore, it is essential for universities and education policymakers to invest in the acquisition, contextual adaptation, and sustainable implementation of cost-effective and pedagogically sound VL platforms tailored to the needs of Ethiopian higher education institutions.

These findings are consistent with previous studies that have reported similar challenges in the adoption of VLs. Deriba et al. (2023) identified infrastructural, pedagogical, and technical limitations in VL implementation. Ngoyi (2013) and Soraya et al. (2022) also highlighted the lack of ICT skills, inadequate training, and limited technical support as critical barriers. Brinson (2015) emphasized the importance of stable internet connectivity, while Kashaka (2024) acknowledged that, despite enhancing student engagement and offering flexible learning opportunities, VLs continue to face challenges related to digital infrastructure, curriculum integration, and the limited development of hands-on skills.

Limitations

This study was conducted at three universities in Southern Ethiopia. While data were collected from both instructors and students, the scope of participants was relatively limited. Additionally, the study focused on immediate outcomes such as perceptions and short-term academic performance, without examining the longer-term effects of VL implementation on students' practical skill development or continued academic progress. These limitations suggest the need for future research to explore the sustained impact of VLs over extended periods. Further studies could also investigate how blended learning models–integrating both VLs and real laboratories–affect students' scientific reasoning, engagement, and hands-on proficiency in chemistry education.

CONCLUSION

This study found that both instructors and students held positive views toward VLs in chemistry education, recognizing their contributions to enhancing academic performance by improving learning quality, strengthening conceptual understanding, and boosting overall student achievement. Additionally, VLs were found to support skill development by promoting problem-solving abilities, facilitating laboratory report writing, and fostering essential scientific skills. Furthermore, these laboratories enhance flexibility and accessibility by supporting self-paced learning and providing practical alternatives when physical laboratories are unavailable.

However, several challenges were identified that hinder the effective implementation of VLs, including limited technical skills, high software costs, insufficient understanding of how to use VLs effectively, and a lack of engaging and interactive platforms. While VLs were appreciated for clarifying complex concepts, they were considered inadequate for developing hands-on practical skills.

Based on these findings, it is recommended that universities invest in digital infrastructure, provide capacity-building programs, and adopt affordable, interactive VL technologies to support their integration as complementary tools alongside traditional laboratory instruction, particularly in resource-constrained environments.

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