Perceived Benefits and Challenges of Virtual Laboratory Implementation in Chemistry Education: A Mixed-Methods Study

Hiwot Bazie, Bekele Lemma, Anteneh Workneh, Ashebir Estifanos

Submitted to: JMIR Medical Education
on: February 26, 2025

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Hiwot Bazie[1] BSc, MSc; Bekele Lemma[2] BSc, MSc, PhD; Anteneh Workneh[2] BA, MA, PhD; Ashebir Estifanos[2] BA, MA, PhD

[1]Hawassa Hawassa University Awasa ET
[2]Hawassa Hawassa University Hawassa ET

Corresponding Author:
Hiwot Bazie BSc, MSc
Hawassa
Hawassa University
Hawassa
Hawassa
Awasa
ET

Abstract

Background: Chemistry education relies heavily on experimentation to bridge theoretical concepts with practical applications. However, universities often face challenges in providing real laboratory experiences due to resource limitations, equipment shortages, and logistical constraints. Virtual laboratories have emerged as a promising alternative, offering interactive, computer-based simulations that replicate real lab experiments and enhance learning.

Objective: This study investigates the perceived benefits and challenges of implementing virtual laboratories in chemistry education at selected universities in Southern Ethiopia, assessing their effectiveness as a teaching and learning tool.

Methods: An explanatory sequential mixed-method design was employed to provide a comprehensive analysis. Quantitative data were collected from 63 chemistry instructors and 143 undergraduate students using structured questionnaires, while qualitative insights were obtained through interviews. Descriptive statistics were used to analyze numerical data, and thematic coding was applied to categorize qualitative responses.

Results: The findings indicate that virtual laboratories significantly enhance chemistry education by improving academic achievement and conceptual understanding, particularly in grasping key concepts and complex topics (average mean score: 3.9). They also contribute to the development of essential scientific skills, such as hypothesis formulation, problem-solving abilities, and effective lab report writing (average mean score: 3.8). Additionally, virtual labs offer flexibility in learning by supporting self-paced education and serving as viable alternatives when access to real laboratories is limited (average mean score: 3.8). However, despite these advantages, several challenges were identified. Limited technical expertise (kappa = 0.63), high software costs (kappa = 0.61), difficulties in understanding specific concepts required for virtual experiments (kappa = 0.61), and the absence of engaging virtual lab software (kappa = 0.51) were among the primary obstacles. Furthermore, a lack of preparedness to address real laboratory challenges (kappa = 0.23) and infrastructural limitations, such as insufficient computer facilities (kappa = 0.25), further hinder the effective implementation of virtual laboratories.

Conclusions: The study underscores the transformative potential of virtual laboratories in chemistry education, serving as viable alternatives to traditional lab instruction. However, their successful implementation requires addressing existing challenges, such as improving digital infrastructure, providing instructor training, and enhancing accessibility. Universities should consider integrating virtual laboratories alongside real labs to optimize learning outcomes and foster technologically advanced educational environments.

(JMIR Preprints 26/02/2025:73148)
DOI: https://doi.org/10.2196/preprints.73148

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Conclusion

The study underscores the transformative potential of virtual laboratories in chemistry education, serving as viable alternatives to traditional lab instruction. However, their successful implementation

requires addressing existing challenges, such as improving digital infrastructure, providing instructor training, and enhancing accessibility. Universities should consider integrating virtual laboratories alongside real labs to optimize learning outcomes and foster technologically advanced educational environments.

Key words: perceived benefits, challenges, virtual laboratories, chemistry education, descriptive survey, Academic performance, Technical expertise

Introduction

Background

Laboratory experiments are essential for linking theoretical knowledge with practical application, enhancing students' understanding of scientific concepts and problem-solving skills [47]. However, in low-income countries like Ethiopia, resource constraints, safety concerns, and logistical challenges often limit hands-on laboratory experiences [20, 42]. As a solution, computer-based laboratories have emerged as viable alternatives, addressing issues such as chemical and equipment shortages in traditional labs [34, 44].

Simulation-based computer laboratories provide safe, interactive, and repeatable environments for experimentation, improving students' grasp of complex scientific principles and enhancing learning outcomes [2, 23]. Research shows that integrating computer-based simulations with traditional lectures significantly boosts students' knowledge, self-efficacy, and motivation [38]. Global studies further highlight their effectiveness in improving comprehension, fostering self-efficacy, and enhancing academic performance [1, 22, and 34]. For instance, [7] found that computer-based laboratories positively impact students' attitudes and academic achievements, while [37] emphasized their role as scalable, flexible, and cost-effective complements to traditional laboratories. Despite these promising findings, the perspectives of instructors and students at regional universities in Ethiopia remain underexplored. Investigating their experiences and attitudes toward Computer-based laboratories is essential for identifying challenges and opportunities to integrate these tools effectively into chemistry education.

While beneficial, implementing computer-based laboratories faces challenges, including limited ICT literacy, inadequate computer skills among students and instructors, software issues, and insufficient training opportunities [35]. Other barriers include poor internet connectivity, high costs, unreliable power supplies, and lack of preparation, further hindering virtual lab adoption [3]. Although existing studies identify these challenges, they do not comprehensively analyze factors affecting the development and integration of computer-based laboratories in Ethiopian universities
Addressing these barriers is vital for advancing chemistry education, particularly as the Ethiopian government prioritizes ICT integration in education policies [33]. The Ethiopian Education Development Roadmap (2018–2030) emphasizes technology use in universities, with progress in adopting ICT tools for teaching and learning [43]. Although some instructors and students use computer-based laboratory resources, such as simulation software and instructional videos, in the absence of physical labs, research on their perceived benefits and challenges remains limited. Given

their flexibility, interactivity, and cost-effectiveness, understanding these perspectives is essential for enhancing virtual lab adoption in resource-limited settings like Ethiopia. Despite the proven effectiveness of virtual laboratories in enhancing students' comprehension, self-efficacy, and academic performance, their adoption in Ethiopian universities remains limited and underexplored. This study seeks to investigate the perceptions and challenges associated with the implementation of virtual laboratories in chemistry education at selected universities. By identifying key barriers the findings will inform institutional policies and strategies to enhance the effective integration of computer-based laboratories in higher education.

Objectives

The general objective of this study was to examine the perceptions of instructors and students regarding computer-based laboratories and the challenges associated with their implementation in chemistry education at universities in southern Ethiopia. The specific objectives were:

1. To evaluate the perceptions of instructors and students regarding the benefits of virtual laboratories in chemistry education.
2. To identify the major challenges in implementing and developing virtual chemistry laboratories at universities in the southern region of Ethiopia.

Literature review

Definition of virtual laboratory

Virtual laboratories (VLs) are computer-based platforms that simulate real-world experiments, enabling students to conduct experiments in a controlled digital environment [17]. These platforms can take the form of two-dimensional (2D) desktop simulations or three-dimensional (3D) virtual reality (VR) settings, offering a flexible and interactive learning experience [40]. VLs integrate interactive elements, data analysis tools, and real-time feedback, providing opportunities for inquiry-based learning and safe experimentation [29]. By allowing asynchronous exploration, VLs support independent or collaborative learning without the need for physical presence, offering exceptional accessibility and flexibility [48]. They are valuable educational resources that help bridge the gap in practical experience and foster engaging, interactive learning [4, 26].

Benefits of virtual lab in science education

Computer-based laboratories play a critical role in enhancing the learning process by bridging theoretical and practical knowledge in science education. They promote interactive, inquiry-based, and cost-effective learning, allowing students to study independently at their own pace and location [26]. Unlike traditional labs that often follow a rigid, protocol-driven approach, Computer-based laboratories foster self-directed exploration and active engagement through trial and error, encouraging students to use their hands, eyes, and minds collaboratively [35]. Research highlights their ability to enhance student knowledge, confidence, and long-term learning outcomes. For example, virtual simulations have been shown to increase engagement and provide flexible access to practical experiences, aligning with the teaching excellence framework in higher education, which emphasizes skill development through hands-on science learning [13].

Challenging in implementing virtual laboratories

Implementing computer-based laboratories in science education presents significant challenges. Key obstacles include inadequate teacher preparation, insufficient training, and low ICT competency among educators and students [35]. Infrastructure issues such as unreliable internet connectivity, unstable electricity, and outdated hardware further complicate integration, particularly in developing countries [3, 25]. Additionally, large class sizes and the time-consuming nature of technology installation exacerbate implementation difficulties [24, 28]. Software failures and frequent technological updates disrupt learning, while the lack of high-speed computers and internet access limits the effectiveness of computer-based laboratories [6]. Addressing these challenges requires investment in infrastructure, comprehensive training, and enhanced digital literacy.

The Effectiveness of Virtual Laboratories on Academic Achievement

Numerous studies have examined the impact of computer-based laboratories on academic performance. [12] Demonstrated that computer-based significantly enhanced understanding and practical skills among hearing-impaired students in electronic circuit experiments. Similarly, [42] found computer-based chemistry laboratories as effective as traditional ones in improving students' conceptual understanding and familiarity with laboratory equipment through visualizations and animations, though no significant differences were noted in reasoning abilities. [1] Reported that virtual simulations improved students' practical chemistry process skills, while [36] highlighted the positive influence of computer-based laboratories on academic achievement and perceptions, with greater effectiveness observed among male students. These findings underscore the potential of computer-based laboratories to enhance learning and practical competencies

Theoretical framework

This study's theoretical framework is grounded in constructivist learning theory, emphasizing active engagement with the environment as central to learning [9, 32]. Computer-based laboratories embody this principle by enabling hands-on experimentation, observation, and the development of scientific inquiry skills within a simulated environment. Vygotsky's social development theory further supports the role of social interaction in enhancing learning, suggesting Computer-based laboratories can facilitate collaboration between students and instructors [27]. The Technology Acceptance Model (TAM) provides additional insight by examining how perceived ease of use and usefulness influence Computer-based laboratory adoption in chemistry education [46]. Within Ethiopian universities, factors such as limited infrastructure, ICT readiness, and resource constraints are critical challenges to computer-based laboratory implementation. Combining constructivism, social learning theory, and TAM, this framework evaluates the potential benefits (e.g., improved learning outcomes and engagement) and barriers (e.g., technical challenges and resistance to change) to adopting VLs in Southern Ethiopian universities.

Conceptual framework

As depicted in Figure 1, the conceptual framework outlines the integration of Computer-based laboratories in chemistry courses, focusing on independent variables such as instructor and student perceptions (positive or negative) and challenges like awareness, technical expertise, and institutional support. These factors influence the dependent variable: the successful implementation of virtual laboratories in chemistry education. Addressing these challenges and fostering positive perceptions are essential for effective integration, which can enhance chemistry education and improve student achievement.

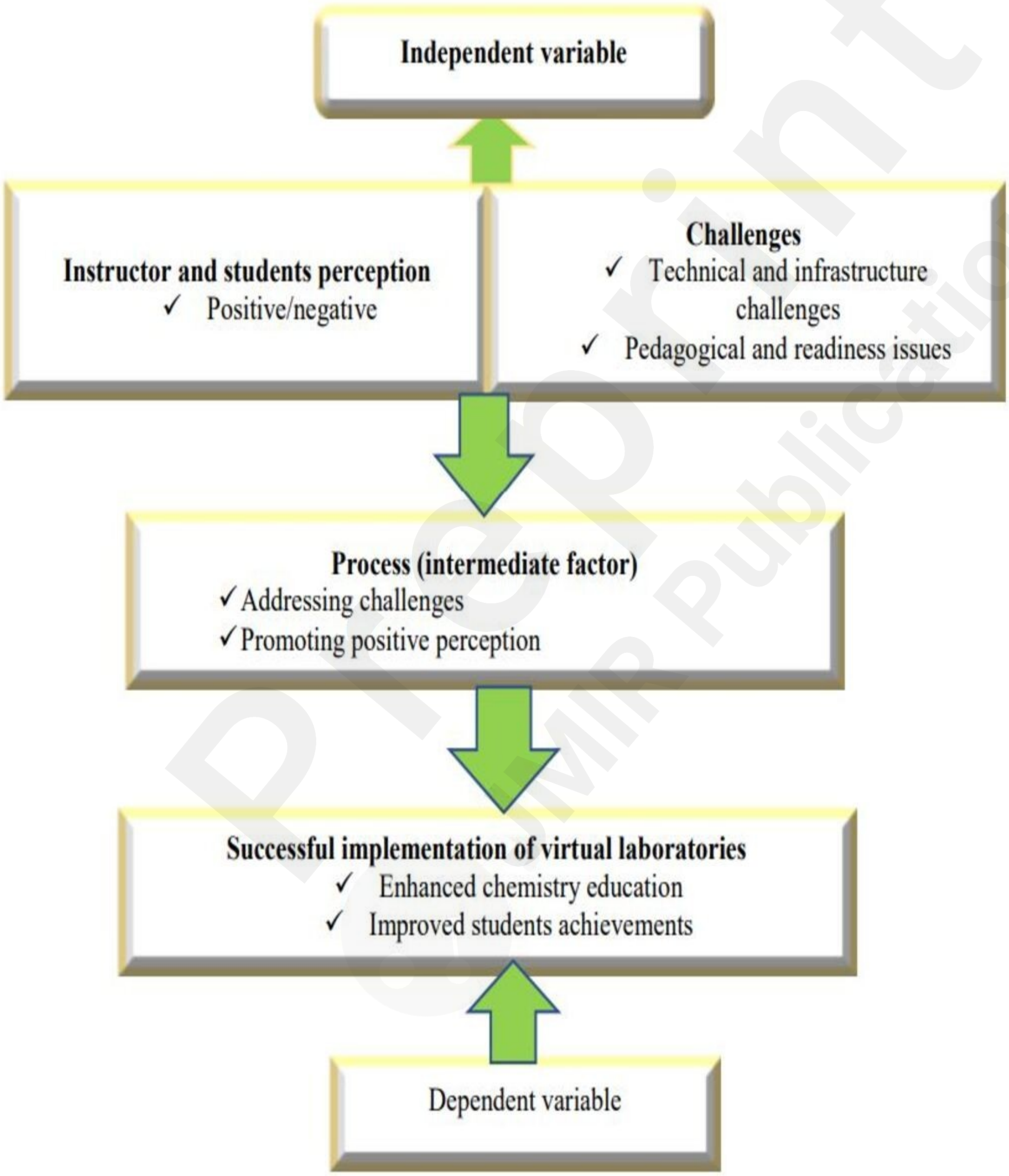

Figure 1. Conceptual framework of the study

Methods

Research Design

This study employed an explanatory sequential mixed-methods design to investigate the perceived benefits and challenges of computer-based laboratories in chemistry education at three universities in Southern Ethiopia: Wolaita Sodo University, Dilla University, and Arbaminch University.

In the first phase, quantitative data were collected via structured questionnaires to identify key challenges, including resource shortages, infrastructure deficits, technical barriers, and limited awareness of virtual labs. This phase also captured perceived benefits, such as enhanced learning flexibility, reduced safety risks, and mitigation of resource constraints. Statistical analysis highlighted measurable trends in participants' responses. The second phase involved semi-structured interviews with a subset of participants to provide deeper context to the quantitative findings. These interviews explored experiences, attitudes, particularly focusing on complex or unexpected results.

This mixed-methods approach ensured a comprehensive analysis, integrating broad statistical trends with nuanced qualitative insights. By combining the strengths of both methods, the study offers actionable recommendations for overcoming barriers and maximizing the potential of virtual laboratories in resource-limited educational environments.

Participants

This study involved chemistry instructors and undergraduate chemistry students from the College of Natural and Computational Sciences at Arba Minch University, Wolaita Sodo University, and Dilla University. The selection process was designed to reflect the unique characteristics and diversity of each group, ensuring comprehensive and generalizable findings.

For chemistry instructors, 50% of the total population from each university was selected using systematic random sampling. This proportion was intentionally chosen to capture the variability within the relatively smaller and more homogenous instructor population, aligning with recommendations for sampling smaller groups [14, 18]. Systematic sampling, a method that minimizes selection bias by giving every individual an equal chance of inclusion, involved selecting participants at fixed periodic intervals based on the population size and desired sample size. As a result, the study included 17 instructors from Dilla University, 18 from Wolaita Sodo University, and 30 from Arba Minch University.

For undergraduate chemistry students, the sample size was calculated using the Krejcie and Morgan formula (Equation 1), a robust and widely recognized approach for determining statistically appropriate sample sizes [16]. Due to the larger and more diverse nature of the student population, stratified sampling was employed to ensure proportional representation across subgroups such as year of study, section, and specialization (e.g., organic or inorganic chemistry). Within each stratum, systematic sampling was applied to select participants proportionally. This method yielded a sample of 57 students from Dilla University, 56 from Wolaita Sodo University, and 71 from Arba Minch University.

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

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

This tailored approach ensured the inclusion of a diverse and representative sample of both instructors and students. The resulting data offer robust insights into the challenges and opportunities for virtual laboratory integration in chemistry education within the Ethiopian higher education context. The target population and sample size are presented in Table 1.

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

Institutions	No. of target population		T. pop.	Sample size (participants)		T. Part.
	Chem.Ins.	Und.Chem.stu.		Chem.Ins. (n,n %)	Und. Chem.stu. (n, n%)	
Dilla university	35	60	95	17 (49%)	57 (95%)	74 (77.9%)
Wolitasodo University	36	59	95	18 (50%)	56 (94%)	74 (77.9%)
Arbaminch University	60	75	135	30 (50%)	71 (95%)	101 (75%)
Total	131	194	325	65 (50%)	184 (95%)	249 (77%)

Note: chem.Ins.= chemistry instructors, Und.Che.stu.= undergraduate chemistry students, T. pop.= total population, T.par.= total participant and n= sample number

Data Collection instrument

This study employed a combination of questionnaires and interviews as primary data collection tools, selected to align with the research objectives and provide both quantitative and qualitative insights. The questionnaire, structured in a closed-ended format, utilized a 5-point Likert scales ranging from strongly disagree to strongly agree. It comprised three sections: demographic information, perceptions of virtual chemistry labs, and challenges in virtual lab implementation. The demographic section collected data on age, gender, education level, and teaching experience, providing essential context for analyzing participants' responses. The second section evaluated the perceived effectiveness, utility, and satisfaction with virtual chemistry labs, offering insights into their impact on teaching and learning. The final section focused on identifying specific challenges, including technical, infrastructural, and resource-related barriers, to better understand obstacles to successful virtual lab integration.

To complement the quantitative data, semi-structured interviews were conducted with a purposefully selected group of five to ten instructors from each university, ensuring diversity in gender, teaching experience, and educational background. These interviews provided an in-depth exploration of instructors' experiences, attitudes, and recommendations regarding virtual laboratories. Participants were informed about the study in advance to build trust and promote candid responses. A consistent set of open-ended questions was used, allowing for systematic comparison while enabling flexibility to delve into individual perspectives. This mixed-method approach ensured a holistic understanding of both the benefits and challenges of virtual chemistry labs, addressing the study's objectives comprehensively.

Validity and Reliability Test of the Research Instruments

To ensure the validity of the questionnaires used in this study, psychology experts reviewed the constructs and content, focusing on the aspects of participants' attitudes toward virtual laboratories and the challenges associated with their implementation and development in chemistry education.

Based on expert feedback, several questionnaire items were revised, rearranged, or removed to improve clarity and relevance, thereby enhancing the instrument's content validity.

For the reliability assessment, a pilot test was conducted with participants from the Department of Chemistry at Kotebe University of Education in Addis Ababa. The pilot data were analyzed, yielding Cronbach's alpha coefficients of 0.839 for the perceived benefits of virtual labs and 0.849 for the challenges associated with their implementation. These coefficients fall within the acceptable range of 0.8 to 0.9, indicating a high level of internal consistency and demonstrating that the instrument is reliable for measuring the intended constructs [21].

Data Collection Procedure

The study was conducted following formal approval from the Department of Chemistry at Hawassa University. Authorization letters were sent to the department heads at the selected universities to request their cooperation. The purpose and significance of the study were clearly communicated to chemistry instructors and students, ensuring their informed, voluntary participation. Participants were selected using a predefined sampling method to ensure a representative sample, and oral consent was obtained from all participants to ensure ethical compliance.

Data collection included the administration of closed-ended questionnaires, which were distributed during face-to-face interactions to facilitate active participation and clarify any ambiguities. Completed questionnaires were promptly returned by participants. Semi-structured interviews were conducted with selected instructors to gain deeper insights into their experiences. These interviews were audio-recorded for accuracy, with additional written notes taken to capture non-verbal cues and contextual information.

To ensure data quality and consistency, responses were carefully reviewed and entered into SPSS version 26 for statistical analysis. Descriptive statistics were used to derive meaningful interpretations and address the study's research objectives, ensuring robust evidence for the study’s conclusions.

Data Analysis Tools and Techniques

To analysis the perceived benefits of virtual laboratories, both qualitative and quantitative analysis methods were employed. For the quantitative analysis, descriptive statistics—such as mean scores, percentages, and frequencies—were used to summarize survey responses collected using a 5-point Likert scale, ranging from "Strongly Disagree" (1) to "Strongly Agree" (5). To aid interpretation, the interval classification method proposed by [11] and [5] was applied, dividing responses into five levels:

- 1.0–1.8: Strongly Disagree
- 1.81–2.6: Disagree
- 2.61–3.4: Neutral
- 3.41–4.2: Agree
- 4.21–5.0: Strongly Agree

This classification provided a clearer understanding of participants' attitudes toward virtual laboratories. Data analysis was conducted by arranging the mean scores in ascending order and presenting them with corresponding frequencies and percentages. The responses from both instructors and students were averaged for each question, and where similar or identical mean values were observed, the combined average was reported. This approach helped minimize individual biases and variability, ensuring a more reliable representation of the overall perception of the group [15]. However, when substantial differences emerged between instructors' and students' responses, the results were analyzed separately to highlight distinct perspectives.

For the qualitative analysis, thematic analysis was conducted on interview transcripts to identify recurring themes. These themes were categorized into broader concepts related to virtual laboratory experiences. The themes were then refined for accuracy, and any patterns, contradictions, or relationships were examined to deepen the understanding of the data. The findings were presented in a narrative format, incorporating direct participant quotes to illustrate key insights.

To analyze the challenges associated with virtual laboratories, in addition to frequency and percentage analysis, a Kappa test was used. The Kappa statistic accounts for agreement beyond chance, making it a more reliable measure than simple percentage comparisons. Kappa values range from -1 to 1, where: 1 indicates perfect agreement, and 0 suggests no agreement beyond chance negative values indicate disagreement [7]. To ensure meaningful comparisons, Kappa was only calculated for items where at least 50% or more of both groups either agreed or disagreed. This approach was necessary due to the unequal sample sizes of instructors (N = 63) and students (N =

143).

For items where less than 50% of either group expressed agreement, the Kappa test was not performed. Instead, these items were analyzed qualitatively to explore potential reasons for differences in perspectives between instructors and students. Table 2 presents the Kappa values

Table 2. Interpretation of Kappa test result

Kappa value	Interpretation
K<0	Less than chance agreement
0≤ k ≤0.20	Poor agreement
0.21≤ k ≤0.40	Fair agreement
0.41≤ k ≤0.60	Moderate agreement
061≤ k ≤0.80	Substantial agreement
0.81≤ k ≤1.00	Almost perfect agreement

Results

Response Rate

As shown in Table 3**,** 63 out of 65 instructors (96.9%) returned their questionnaires, demonstrating strong participation. Among students, 143 out of 184 (77.7%) responded, indicating substantial involvement. Overall, 206 out of 249 participants (86.3%) completed the survey, exceeding the 70% threshold considered acceptable for analysis [10]. This response rate is deemed adequate for the study's analysis.

Table 3. Response Rate

Respondents	Sample size	Returned questionnaires	returned rate in %
Instructors	65	63	96.9
Students	184	143	77.7
Total	249	206	86.3

Respondents characteristics

The demographic profile of respondents indicates that 58 out of 63 instructors (92%) were male, while 5 out of 63 (8%) were female. In terms of age, 27 instructors (43%) were between 31-40 years, followed by 22 (35%) aged 41-50, 10 (16%) aged 21-30, and 4 (6%) over 50. Regarding qualifications, 39 instructors (62%) held a Master's degree, 20 (32%) had a Ph.D., and 4 (6%) had a Bachelor's degree. Teaching experience varied, with 21 instructors (33%) having 11-15 years of experience, 19 (30%) with 6-10 years, 9 (14%) with 16-20 years, 11 (17%) with more than 20 years, and 3 (5%) with less than 5 years of experience.

Among students, 124 out of 143 (87%) were male, while 19 (13%) were female. Most students (128 out of 143, or 90%) were between 21-23 years old, while 9 (6%) were aged 24-27, 5 (3%) were 18-20, and 1 (1%) was 28-30. In terms of academic level, the majority (92 students, or 64%) were in their fourth year, followed by 40 (28%) in their third year and 11 (8%) in their second year.

Overall, the data reflect a predominantly male group of instructors and students. Instructors generally held advanced degrees and had significant teaching experience, while most students were in their final year of study. This demographic profile provides a relevant basis for analyzing the study's findings.

Table 4. Respondent's Demography Profile

No.	**Item**		**Respondents**			
			Chem. Inst. (N= 63)		**Und. Chem. Stud.(N= 143)**	
			n	n(%)	n	n(%)
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	Ph.D/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		

Note: Chem.Inst. = chemistry instructors, Und. Chem. Stud. = undergraduate chemistry students, f. = frequency

Perceptions of Instructors and Students on the Benefits of Virtual Laboratories
Quantitative insight from instructors and students

Ease of Use and Understanding

As shown in Table 5, for item Atvd1, both instructors and students had a mean score of 2.3, falling within the "disagree" range (1.81–2.6). This suggests that most participants do not believe the virtual laboratory hinders student preparation for the next lab session, with 70% of instructors (44 out of 63) and 67.9% of students(97 out of 143) disagreeing. For item Atvd2, instructors and students had mean scores of 2.4 and 2.6, respectively, also within the "disagree" range. This indicates that most participants do not find virtual labs difficult to follow, with 57% of instructors (36 out of 63) and 57.4% of students (82 out of 143) disagreeing.

Table 5. Descriptive Statistics on Attitudes toward Ease of Use and Understanding of Virtual laboratories

Items code	Item description	Mean (M)	Number and percentage	group
$Atvd_1$	The virtual laboratory does not assist students in preparing for the next lab session	2.3	44 out of 63 (70%)	Instructors
		2.3	97 out of 143 (67.9%)	students
$Atvd_2$	Teaching or learning practical chemistry courses (experiments) with virtual laboratory makes it difficult to follow and understand the concept	2.4	36 out of 63 (57%)	Instructors
		2.6	82 out of 143 (57.4%)	students

Note: $Atvd_1$–$Atvd_2$ reflect attitudes toward the ease of use and conceptual understanding of virtual labs, with lower mean scores indicating disagreement

As shown in Table 6, the mean score for item code Atvn1 was 3.4, with 14 out of 63 instructors (22%) selecting this response. This falls within the 2.61–3.4 range, indicating a neutral level of agreement, suggesting that instructors are unsure about the effectiveness of virtual labs in boosting students' interest in learning chemistry. Similarly, the mean score for Atvn2 was also 3.4, with 27 out of 143 students (18.9%) selecting this response, reflecting a neutral stance among students regarding whether virtual labs offer more teaching options in less time and improve engagement.

Table 6. Descriptive Statistics on Perceived Interest and Flexibility in Virtual Laboratory Learning

Items	Item description	Mean	Number and	Group

code		(M)	percentage	
$Atvn_1$	Using a virtual laboratory for practical chemistry enhances students' interest in learning chemistry.	3.4	14 out of 63 (22%)	Instructors
$Atvn_2$	Virtual laboratories offer greater flexibility and interactive learning opportunities in a shorter time	3.4	27 out of 143 (18.9%)	Students

Effectiveness of Virtual Laboratories in Enhancing Chemistry Teaching and Learning

The overall mean score for Atva1–Atva10 is 3.8, falling within the 3.41–4.2 range, indicating an "agree" level among instructors and students (Table 7). On average, 47 out of 63 instructors and 111 out of 143 students (75.6%) expressed agreement, confirming a strong positive perception of virtual laboratories. These findings highlight their recognized benefits, including improved educational quality, enhanced student achievement, and effectiveness as alternatives to real laboratories. Virtual labs also support continuous learning, scientific skill development, problem-solving, and flexible, self-paced learning.

Learning interest, interaction and engagement

The mean score for $Atva_{11}$ was 4.0**,** indicating a high level of agreement, with 81.9% of students (117 out of 143) acknowledging that virtual laboratories enhance their interest in learning chemistry (Table 7). Similarly, $Atva_{12}$ had a mean score of 3.8, reflecting strong agreement, as 78% of instructors (49 out of 63) agreed that virtual labs offer more teaching options in less time while enhancing student-instructor interaction**.**

Table 7. . Descriptive Statistics on attitude toward the effectiveness of Virtual Laboratory Learning

Items code	Item description	Mean (M)	Number and percentage	Group
$Atva_1$	Teaching or learning chemistry courses via virtual learning enhances the quality of learning chemistry	3.9	48 out of 63 (76%)	Instructors
		4.0	118 out of 143 (82.6%)	students
$Atva_2$	Teaching or learning practical chemistry course (experiments) with virtual laboratory increase students' achievement level.	3.7	44 out of 63 (70%)	Instructors
		3.9	105 out of 143 (73.5%)	students
$Atva_3$	Using virtual laboratory in the teaching and learning process enable the instructors and students to improve their understanding, and teaching and learning skills	3.7	47 out of 63 (75%)	Instructors
		3.9	109 out of 143 (76.3%)	students

Atva$_4$	A virtual laboratory (a computer-based laboratory) is a helpful tool for students and teachers when conducting chemistry experiments in a real laboratory is not possible	3.9	48 out of 63 (76%)	Instructors
		4.0	117 out of 143 (82.1%)	students
Atva$_5$	Instead of skipping lab experiments, teaching experiments using a virtual chemistry lab makes it easier for students to understand the concepts	3.8	45 out of 63 (72%)	Instructors
		4.0	115 out of 143 (80.5%)	students
Atva$_6$	Teaching or learning practical chemistry course (experiments) by utilizing with virtual laboratory enhance students' scientific skills	3.9	51 out of 63 (81%)	Instructors
		3.9	107 out of 143 (74.9%)	students
Atva$_7$	Teaching or learning practical chemistry through virtual laboratory allows students to developing students own hypothesis and enhancing problem-solving methods	3.6	39 out of 63 (62%)	Instructors
		3.8	104 out of 143 (72.8%)	students
Atva$_8$	Teaching or learning practical chemistry through virtual laboratory allows students to write lab reports easily because they can repeatedly watch	3.8	48 out of 63 (76%)	Instructors
		3.9	118 out of 105 (73.5%)	students
Atva$_9$	Teaching or learning practical chemistry courses (experiments) with virtual laboratory allows students to understand the complex concept of chemistry	4.0	52 out of 63 (82%)	Instructors
		3.9	107 out of 143 (74.8%)	students
Atva$_{10}$	Teaching or learning practical chemistry courses (experiments) with a virtual laboratory permits students to develop self-paced learning	3.9	47 out of 63 (75%)	Instructors
		3.9	113 out of 143 (79%)	students
Atva$_{11}$	Teaching or learning practical chemistry courses via virtual laboratory provides teachers and students with more options in shorter time with interaction	3.8	49 out of 63 (78%)	Instructors
Atva$_{12}$	Teaching or learning practical chemistry courses (experiments) with virtual laboratory increases students' interest in learning chemistry	4.0	117 out of 143 (81.9%)	Students

Note: *Note: Atva$_1$–Atva$_{12}$ reflects attitudes toward* effectiveness of Virtual Laboratory Learning*, with higher mean scores indicating an agreement.*

Qualitative Insights from Instructor Interviews

The qualitative analysis of instructor interviews provided in-depth perspectives on the role of virtual laboratories in chemistry education, complementing the survey findings. Instructors generally recognized the benefits of virtual labs in enhancing conceptual understanding and enabling independent experimentation, particularly in situations where access to physical laboratories is limited. However, opinions varied regarding the extent to which virtual laboratories could serve as a full replacement for traditional hands-on experiences.

Key Themes

Irreplaceability of Real Laboratories

All instructors unanimously agreed that physical laboratories remain essential for hands-on learning, particularly for skills involving direct chemical handling and experimental procedures.

Virtual Laboratories as Effective Alternatives

A majority of instructors (95%) considered virtual laboratories to be viable alternatives when logistical or resource constraints limit access to physical labs, ensuring continuity in practical learning.

Complementary Role in Chemistry Education

Approximately 60% of instructors emphasized that virtual labs should not replace real laboratories but should instead serve as supplementary tools. They highlighted their usefulness in helping students prepare for physical lab sessions and reinforcing learning after hands-on experiments.

Enhanced Conceptual Understanding

Most instructors (85%) reported that virtual labs facilitate the comprehension of complex chemistry concepts, making them effective for theoretical reinforcement.

Limitations in Hands-On Skill Development

A subset of instructors (40%) expressed concerns that virtual labs do not fully replicate the hands-on skills gained in physical laboratories, emphasizing the need for an integrated approach that balances both virtual and real lab experiences.

Divergent Perspectives

Instructor opinions on the broader applicability of virtual labs varied:

Respondent Y (Arbaminch University) argued that simulation virtual labs could entirely replace real labs in improving skills and comprehension, even without physical interactions like handling or burning chemicals.

Respondent X (Wolaita Sodo University) highlighted the potential of virtual labs to advance science education by simplifying complex concepts and developing essential skills. However, they attributed the limited adoption of virtual labs to a lack of stakeholder motivation and called for greater awareness and support for their integration

Challenges to implement and develop virtual laboratory in chemistry education

Lack of Awareness (Cv1)

As shown in Table 8, for item Cv1, the majority of instructors (46 out of 63; 73%) did not view a lack of awareness as a significant barrier to implementing virtual laboratories. However, 34 instructors (54%) recognized awareness as a challenge, while 4 instructors (6%) remained neutral. Among the 143 students surveyed, 78 (54%) considered a lack of awareness a major challenge, while 45 (31%) disagreed, and the remaining 20 (14%) were neutral.

Perception of Virtual Labs as Non-Essential (Cv2)

For item Cv2, 36 out of 63 instructors (57%) disagreed with the idea that virtual labs are unnecessary for learning practical chemistry, while 12 (19%) believed they were non-essential. The remaining 4 instructors (6%) were neutral. Among the 143 students, 60 (42%) disagreed with the notion, while 42 (29%) agreed. The remaining 16 students (11%) were neutral (Table 8).

Concern about understanding concept through virtual laboratory (Cv3)

Regarding item Cv3, 42 out of 63 instructors (67%) disagreed with the statement that virtual labs make it harder to understand chemistry concepts, while 14 (22%) agreed. The remaining 7 instructors (11%) were neutral. Among students, 87 out of 143 (61%) disagreed with the concern, while 29 (20%) agreed. The remaining 27 students (19%) were neutral (Table 8).

Table 8. Descriptive statistics result of challenges with respect to awareness and perception

items code	items description	Response type	Instructors (N=63) n (n%)	Students (N=143) n (n%)	Kappa value
Cv_1	Chemistry instructors, lab technicians and	Strongly agree(SA) Agree(A)	2(3.2) 11(17.5)	20(14.0) 58(40.6)	---

	students are not aware of the existence of a virtual laboratory	Neutral (N)	4(6.3)	20(14.0)	
		Disagree (DA)	32(50.8)	30(21.0)	
		Strongly disagree(SD)	14(22.2)	15(10.5)	
Cv_2	Assuming that it doesn't matter whether you teach/ learn a practical chemistry course using a virtual laboratories or not because virtual labs don't replace real laboratories	Strongly agree(SA)	1 (1.6)	15(10.5)	-----
		Agree(A)	11(17.5)	27(18.9)	
		Neutral (N)	4(6.3)	16(11.2)	
		Disagree (DA)	18(28.6)	30(21.0)	
		Strongly disagree(SD)	18(28.6)	30(21.0)	
Cv_3	Believing that the idea that teaching/learning practical chemistry through virtual laboratories makes it harder to fully understand the concepts	Strongly agree(SA)	4(6.3)	6(4.2)	----
		Agree(A)	10(15.9)	23(16.1)	
		Neutral (N)	7(11.1)	27(18.9)	
		Disagree (DA)	35(55.6)	59(41.3)	
		Strongly disagree(SD)	7 (11.1)	28(19.6)	

Lack of knowledge on how to use virtual laboratories (Cv4)

As shown in Table 9, 50 out of 63 instructors (79%) did not view a lack of knowledge on how to use virtual chemistry labs as a major challenge, while 9 (14%) acknowledged it as an issue. The remaining 4 instructors (6%) were neutral. Among the 143 students, 77 (54%) considered this a challenge, while 31 (22%) disagreed. The remaining 35 students (25%) were neutral. These findings suggest that while instructors feel confident using virtual labs, many students face difficulties with this aspect.

Lack of understanding of key concepts for virtual experiments (Cv5)

Regarding the lack of understanding of certain concepts required to perform experiments in a virtual chemistry lab, 43 out of 63 instructors (68%) agreed that this was a challenge, while 17 (27%) disagreed. The remaining 3 instructors (5%) were neutral. Among the 143 students, 118 (82.5%) viewed this issue as a challenge, while 15 (10.5%) disagreed. The remaining 10 students (7%) were neutral. The kappa value of 0.61 indicates substantial agreement between instructors and students on this issue, suggesting that both groups recognize the difficulty of grasping certain concepts in a virtual environment.

Lack of Technical Expertise (Cv6)

A total of 50 out of 63 instructors (79%) acknowledged that a lack of technical expertise is a significant challenge to implementing and developing virtual laboratories in chemistry education, while 10 instructors (16%) disagreed. The remaining 3 instructors (5%) were neutral (Table 9). Among the 143 students, 111 (77.6%) considered technical expertise a major obstacle, while 22 students (15.4%) disagreed. The remaining 10 students (7%) were neutral. The kappa value of 0.63 suggests substantial agreement between instructors and students, reinforcing the idea that limited technical proficiency in using virtual laboratory is a widespread concern.

Table 9. Descriptive statistics result of challenges with respect Technical challenges

items code	items description	Response type	Instructors (N=63) n (n%)	Students (N=143) n (n%)	Kappa value
Cv_4	Not knowing how to teach/learn using virtual chemistry lab	Strongly agree(SA)	1(1.6)	14(9.8)	---
		Agree(A)	8(12.6)	63(44.1)	
		Neutral (N)	4 (6.3)	35(24.5)	
		Disagree (DA)	37 (58.7)	22(15.4)	
		Strongly disagree(SD)	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(SA)	12 (19.04)	40(28)	0.61
		Agree(A)	31(49.2)	78(54.5)	
		Neutral (N)	3(11.1)	10(6.9)	
		Disagree (DA)	10(15.9)	11(7.7)	
		Strongly disagree(SD)	7 (11.1)	4(2.8)	
Cv_6	Instructors and students lack technical expertise to operate virtual lab software effectively	Strongly agree(SA)	5 (7.9)	26(18.2)	0.63
		Agree(A)	45(71.4)	85(59.4)	
		Neutral (N)	3 (4.8)	10(6.9)	
		Disagree (DA)	8(12.6)	12(8.4)	
		Strongly disagree(SD)	2 (3.2)	10(7.0)	

High Cost of Developing and Acquiring Virtual Lab Software (Cv7)

As shown table 10, among instructors, 43 (68%) agreed that the high cost of developing and acquiring virtual lab software is a significant barrier. Meanwhile, 9 instructors (14%) disagreed, and 11 (18%) remained neutral. Similarly, 87 students (61%) viewed cost as a barrier, while 20 students (14%) disagreed. The remaining 36 students (25%) were neutral. The kappa value of 0.61 indicates a substantial agreement between instructors and students.

Lack of Awareness of Virtual Laboratory Resources (Cv8)

Among instructors, 24 (38%) acknowledged that they do not know the sources of virtual laboratory resources, whereas 29 (46%) disagreed implying that lack of awareness is not a significant barrier among them. The remaining 10 instructors (16%) were neutral. In contrast, a higher proportion of students (40%) agreed with this challenge, while 39 students (27%) disagreed. The largest proportion of students (53 or 38%) remained neutral (Table 10)

Lack of Interesting Software in Available Computer Programs (Cv9)

A total of 49 instructors (78%) agreed that the lack of engaging and relevant software is a problem, while 7 (11%) were neutral, and 7 (11%) disagreed (Table 10). Among students, 91 (64%) also perceived this as a challenge, while 20 students (14%) disagreed. The remaining 32 students (22%) were neutral. The kappa value of 0.51 indicates moderate agreement between instructors and students.

Table 10. Descriptive statistics result of challenges with respect Resource constraint

items code	items description	Response type	Instructors (N=63) n (n%)	Students (N=143) n (n%)	Kappa value

Cv_7	The high cost of developing and acquiring virtual lab software is a significant barrier for institutions	Strongly agree(SA) Agree(A) Neutral (N) Disagree (DA) Strongly disagree(SD)	10(15.9) 33(52.4) 11(17.5) 6(9.5) 3(4.8)	22(15.4) 65(45.5) 36(25.2) 11(7.7) 9(6.3)	0.61
Cv_8	Instructors do not know the sources of virtual laboratory	Strongly agree(SA) Agree(A) Neutral (N) Disagree (DA) Strongly disagree(SD)	3 (4.8) 21(33.3) 10(15.9) 25(39.7) 4 (6.3)	27(18.9) 31(21.7) 53(37.5) 27(18.9) 12(8.4)	-----
Cv_9	Lack of interesting software in a set of computer programs	Strongly agree(SA) Agree(A) Neutral (N) Disagree (DA) Strongly disagree(SD)	10(15.9) 39(61.9) 7(11.1) 5 (7.9) 2 (3.2)	32(22.4) 59(41.3) 32(22.4) 12(8.4) 8(5.6)	0.51

Instructor Readiness to Use Virtual Laboratories (Cv10)

As shown in Table 11, among instructors, 38 out of 63 (60%) agreed that they are not ready to use virtual laboratories as a solution to real lab challenges, while 23 (36.4%) disagreed. A small portion (4 instructors, 6%) remained neutral. Similarly, 82 out of 143 students (57%) believed that instructors are not ready, while 27 (19%) disagreed. Meanwhile, 34 students (24%) were neutral on the matter. The kappa value of 0.23 indicates a fair level of agreement between instructors and students, suggesting that their perceptions of instructor readiness are somewhat aligned.

Motivation of Stakeholders to Use Virtual Laboratories (Cv11)

Among instructors, 30 out of 63 (48%) agreed that stakeholders are not motivated to use virtual laboratories, while 29 (46%) disagreed. The remaining 8 instructors (13%) were neutral. Among students, 56 out of 143 (39%) believed that stakeholders lack motivation, while 39 (27%) remained neutral, and 39 (27%) disagreed (Table 11).

Table 11. Descriptive statistics result of challenges with respect Motivation and readiness

items code	items description	Response type	Instructors (N=63) n (n%)	Students (N=143) n (n%)	Kappa value
Cv_{10}	Instructors are not ready to use virtual laboratories to overcome problems associated with real lab experiments	Strongly agree(SA) Agree(A) Neutral (N) Disagree (DA) Strongly disagree(SD)	9 (14.28) 29(46.0) 4(6.3) 16(25.3) 7 (11.1)	19(13.3) 63(44.1) 34(23.8) 22(15.4) 5(3.5)	0.23
Cv_{11}	Stakeholders are not motivated to use virtual laboratory	Strongly agree(SA) Agree(A) Neutral (N) Disagree (DA) Strongly disagree(SD)	7 (11.1) 23(36.5) 8 (12.7) 25(39.7) 4 (6.3)	19(13.3) 37(25.9) 39(27.3) 27(18.9) 12(8.4)	-----

Perceptions on the Need for Virtual Laboratories (Cv12)

Among instructors, 72% (47 out of 63) disagreed or strongly disagreed with the statement that virtual laboratories are unnecessary due to well-equipped chemistry labs. A similar trend was observed among students, with 61% (87 out of 143) also disagreeing. However, a small proportion of both instructors (13%) and students (30%) expressed agreement, indicating that some still believe existing facilities are sufficient (Table 12).

Challenges Due to Poor Internet Connectivity (Cv13)

Among instructors, 38% agreed or strongly agreed, while 46% disagreed, revealing a somewhat divided perception. Among students, 41% shared this concern, while 37% remained neutral. The high level of neutrality among students suggests uncertainty or variability in internet access across different university settings (Table 12)..

Lack of Dedicated Computer Labs (Cv14)

The kappa value of 0.25 indicates fair agreement between instructors and students regarding the absence of dedicated computer labs for virtual experiments. Among instructors, 54% (34 out of 63) agreed or strongly agreed that their department or college lacks a computer lab, while **33% (21 out of 63)** disagreed. Similarly, 58% (88 out of 143) of students shared this concern, whereas 30.1% (43 out of 143) disagreed.

Research Gap on Virtual Labs in Ethiopia (Cv15)

As depicted in table 12, among instructors (52%, 33 out of 63) and students (44%, 63 out of 143) agreed that the lack of research on virtual laboratories in Ethiopia makes their impact on student achievement unclear. Meanwhile, 27% of instructors (17 out of 63) and 17% of students (24 out of 143) remained neutral, reflecting uncertainty about the extent of existing research. Disagreement levels were moderate, with 21 instructors (33%) and 56 students (39%) disagreeing or strongly disagreeing, suggesting that while some acknowledge research efforts, a considerable gap remains in evaluating the effectiveness of virtual labs in the Ethiopian education system

Table 12. Descriptive statistics result of challenges with respect infrastructure and research gap

items code	items description	Response type	Instructors (N=63) n (n%)	Students (N=143) n (n%)	Kappa value

Cv_{12}	No need of using a virtual laboratory since there are well equipped chemistry laboratories	Strongly agree(SA)	1 (1.6)	18(12.6)	---
		Agree(A)	7 (11.1)	26(18.2)	
		Neutral (N)	1 (1.6)	12(8.4)	
		Disagree (DA)	30(47.6)	42(29.4)	
		Strongly disagree(SD)	24(38.1)	45(31.5)	
Cv_{13}	Poor university internet connectivity hinders the use of computer-based laboratories	Strongly agree(SA)	3 (4.8)	27(18.9)	-----
		Agree(A)	21(33.3)	31(21.7)	
		Neutral (N)	10(15.9)	53(37.5)	
		Disagree (DA)	25(39.7)	27(18.9)	
		Strongly disagree(SD)	4 (6.3)	12(8.4)	
Cv_{14}	The department or college lacks a dedicated computer lab for conducting virtual experiments	Strongly agree(SA)	12(19.0)	44(30.0)	0.25
		Agree(A)	22(34.9)	40(28.0)	
		Neutral (N)	8 (12.7)	16(11.2)	
		Disagree (DA)	20(31.7)	29(20.3)	
		Strongly disagree(SD)	1 (1.6)	14(9.8)	
Cv_{15}	The lack of research on virtual labs in Ethiopia makes their impact on student achievement unclear.	Strongly agree(SA)	7 (11.1)	16 (11.2)	------
		Agree(A)	26(41.3)	47(32.9)	
		Neutral (N)	17(27.0)	24(16.8)	
		Disagree (DA)	10(15.9)	36(25.2)	
		Strongly disagree(SD)	3 (4.6)	20(14.0)	

Discussion

Overview

This study explored instructors' and students' perceptions of virtual laboratories in chemistry education, highlighting both their benefits and challenges. The findings indicate strong support for virtual labs as effective tools for enhancing academic achievement, conceptual understanding, and skill development. However, key challenges such as technical proficiency, resource limitations, and infrastructural constraints were identified, suggesting the need for targeted training and institutional support. The study also highlights that while virtual labs serve as a valuable supplement to real laboratories, they are not universally accepted as a complete replacement. These insights underscore the necessity of a well-balanced integration strategy that maximizes the advantages of virtual labs while addressing their limitations.

Principal finding

Perceptions of Instructors and Students on the Benefits of Virtual Laboratories

The results indicate that both instructors and students recognize the valuable role of virtual laboratories in enhancing chemistry education. High agreement levels were observed regarding their effectiveness in improving academic achievement and conceptual understanding (e.g., achievement level, quality of learning chemistry, ease of understanding concepts, and grasping complex topics; average mean = 3.9). Similarly, virtual labs were acknowledged for enhancing skill development and scientific inquiry (e.g., scientific skills, hypothesis development, problem-solving abilities, and ease of writing lab reports; average mean = 3.8) and providing flexibility in learning approaches (e.g., teaching and learning skills, self-paced learning, and serving as an alternative when real laboratories are unavailable; average mean = 3.8). These findings suggest that virtual laboratories serve as an effective supplement to traditional laboratory instruction, particularly in settings where access to physical lab resources is limited.

The interview data further reinforced these findings, with 95% of instructors acknowledging virtual labs as valuable in settings with limited laboratory resources. However, 60% emphasized that virtual labs should complement, rather than replace, real laboratories. While most instructors (85%) agreed that virtual labs simplify complex concepts, 40% expressed concerns about their limited ability to develop hands-on practical skills.

Challenges to Implementation

The study revealed several key challenges to the implementation of virtual laboratories in chemistry education. These challenges primarily include technical proficiency, conceptual understanding, resource constraints, and infrastructural limitations. The analysis of Kappa values for items Cv5, Cv6, Cv7, Cv9, Cv10, and Cv14 (ranging from 0.61 to 0.25) demonstrated fair to substantial agreement between instructors and students regarding these barriers. Specifically, the major obstacles identified were a lack of technical expertise, high costs associated with software acquisition or development, the absence of engaging virtual lab software, and difficulties in understanding certain concepts essential for the development and implementation of virtual laboratories. Additionally, inadequate preparedness to address real laboratory challenges and the lack of computer facilities within departments or colleges were also highlighted as significant constraints.

Awareness and knowledge gaps: While 73% of instructors did not view awareness as a major barrier, 54% of students identified it as a challenge, suggesting a need for targeted awareness programs.

Infrastructure limitations: Poor internet connectivity was cited as a barrier by 38% of instructors and 41% of students. Additionally, 52% of instructors and 44% of students emphasized the lack of research on virtual lab effectiveness in Ethiopia, indicating the need for further studies.

Conceptual understanding: The study found that 67% of instructors and 61% of students disagreed that virtual labs hinder comprehension. However, 20% of students reported difficulties, highlighting the need for additional instructional support.

Comparison with Prior Work

The findings of this study align with previous research on the effectiveness of virtual laboratories in chemistry education. The previous study, such as Lamb et al.[30], Al Hassan [49], Bazie et al. [50] and Rosli and Ishak [51] have confirmed that virtual laboratories contribute significantly to students' conceptual understanding, academic achievement, science process skills and problem-solving abilities. The positive perceptions observed in this study imply that integrating virtual laboratories into chemistry education can not only bridge resource gaps but also promote self-paced learning and skill acquisition, ultimately improving the overall quality of science education. Miyamoto et al.[53] emphasized the role of virtual laboratories in enhancing students' practical skills and reinforcing fundamental experimental procedures,

The challenges identified in this study align with previous research on virtual laboratory implementation. Prior studies have also recognized technological, infrastructural, pedagogical, and cultural challenges as significant barriers to adoption Deriba, et al.,[19]. Similarly, Ngoyi [35] and Soraya et al. [52] identified key obstacles to virtual lab implementation, including insufficient ICT skills, software limitations, inadequate training, and a lack of technical expert. Brinson [54] identified internet access and technological infrastructure as crucial factors affecting the successful implementation of virtual laboratories, while Smetana and Bell [55] stressed the need for reliable infrastructure and ongoing research to evaluate the educational impact of virtual labs. These findings collectively underscore the necessity for improved resources, enhanced technical support, and further research to optimize virtual lab integration in chemistry education.

Conclusion

This study Accentuate the perceived benefits and challenges of implementing virtual laboratories in chemistry education. The findings emphasize that virtual laboratories play a crucial role in enhancing chemistry learning by improving academic achievement and conceptual understanding, including better comprehension of key concepts and complex topics. They also contribute to the development of scientific skills, such as hypothesis formulation, problem-solving abilities, and effective lab report writing. Additionally, virtual labs offer flexibility in learning by supporting self-paced education and serving as viable alternatives when access to real laboratories is limited.

Despite their numerous benefits, several challenges were identified in the study. These obstacles include limited technical expertise, high software costs, difficulties in understanding certain concepts necessary for conducting virtual experiments, and the absence of engaging virtual lab software.

Additionally, a lack of preparedness to address real laboratory challenges, along with infrastructural limitations such as insufficient computer facilities, further hinders the effective implementation of virtual laboratories. While virtual laboratories are highly regarded for their ability to simplify complex concepts, concerns remain regarding their limitations in fostering hands-on practical skills. To maximize the impact of virtual laboratories, universities should adopt a balanced approach by integrating them as complementary tools alongside real laboratories. Addressing key barriers, such as improving technical training, investing in high-quality virtual lab software, and expanding access to computer resources, will be essential for ensuring their successful implementation.

Limitation

The study was conducted at three universities in Southern Ethiopia, and its findings may not fully reflect the challenges and perceptions of other institutions within Ethiopia or globally. Although both instructors and students participated, the sample size may limit the generalizability of the results to a wider population. Additionally, the study was conducted within a specific timeframe and did not evaluate the long-term impact of virtual laboratories on student performance and skill development.

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