

Design, Development and Evaluation of ... Adediran, T. D. & Oke, A. A. (2025)

Design, Development and Evaluation of web-based Virtual Laboratory for Integrated Science Education Program among Selected Colleges of Educations in Osun State, Nigeria

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Abstract

The effective training of science student-teachers is critical for the advancement of science-based education. Traditional laboratory instruction still faces challenges related to high cost, safety issues, and accessibility. This study focuses on the design, development and evaluation of a web-based Virtual Laboratory (VL) designed to enhance the training of student-teachers in integrated science teachers. The study uses a quantitative approach, where 120 student-teachers were assessed before and after a four-week intervention with the developed Virtual Laboratory. Quantitative analysis showed a statistically significant increase in competency scores from pre-test ($M = 64.5$, $SD = 8.2$) to post-test ($M = 85.3$, $SD = 7.5$), $t(149) = 21.8$, $p < .001$. The study implemented a System Usability Scale (SUS) which showed a mean score of 88.5, indicating excellent student satisfaction with the Laboratory. The study findings shows that the VL is an effective and usable tool that significantly improves student-teachers' practical knowledge and teaching confidence.

Keywords: Virtual Laboratory, Integrated Science Education, Teacher Training, Educational Technology, Usability.

Introduction

Science education for student teachers relies on laboratory experimentation, where students observe scientific concept, verify theoretical principles, and also develop the necessary practical skills (Kurtz et al., 2025). Laboratory experimentations provides opportunities for students to develop knowledge through the direct use of laboratory equipment's and observation of results (Bitar et al., 2024). In the field of Integrated Science Education in Colleges of Education in Nigeria, laboratory work is indispensable for developing practical skills and conceptual understanding. Traditional physical laboratories often face constraints such as high operational costs, safety issues, and limited access. Studies have shown that there is increase need for virtual laboratories not merely as a supplementary tool but as a critical infrastructure needed to ensure pedagogical continuity (Oun et al., 2025). By leveraging Virtual Laboratories, it would provide a risk-free environment where students can iterate experiments, visualize molecular interactions, and reduce the gap between theory and practical observation. In many institutions, particularly in developing countries like Nigeria, the lack of adequate resources and infrastructure for practical science education is a significant challenge. The absence of well-equipped science laboratories in schools often limits the effectiveness of science teaching and learning (Efendi & Jayanti, 2024). This gap is even more pronounced in teacher training programs, where Nigeria Certificate in Education (NCE) students may not have access to hands-on practical experience in science education (Babalola & Fakoyede, 2022). Even with adequate equipment, effective science teaching requires teachers to be well-trained in designing and implementing engaging laboratory activities (Remperas et al., 2025; Zhang et al., 2024). This study therefore aims to design and develop a Virtual Laboratory (VL) that will serve as a simulation tool for science experiments and activities, for student teachers in colleges of education in Nigeria to gain practical knowledge and experience in conducting integrated science experiments.

Objectives of the Study

The objectives of the study are to:

1. Design a Virtual Laboratory for NCE students in Integrated Science Education
2. Develop the designed Virtual Laboratory for NCE students in Integrated Science Education
3. Assess the usability and accessibility of the VL in different educational settings



Design, Development and Evaluation of ... Adediran, T. D. & Oke, A. A. (2025)

Research Questions

The following research questions guided the study:

1. How effective is the Virtual Laboratory in enhancing NCE students' practical skills in integrated science education?
2. What are the perceptions of student-teachers regarding the usability and accessibility of the Virtual Laboratory?
3. How does the use of the Virtual Laboratory influence the teaching competency of NCE Students?

Literature Review

Research has indicated that the VL teacher training programs may have a positive effect on the perceptions, attitudes and learning outcomes of participants in the VL use (Achuthan et al., 2023). The teachers who were exposed to VLs prior to teaching show better knowledge of various educational practices and are more participatory in the physical lab work (Alhashem & Alfaiakawi, 2023). VL are considered to be efficient as supplementary devices in the development of skills and knowledge transfer of laboratories in blended classrooms (Radhamani et al., 2018).

Virtual Laboratories in Education

Virtual laboratories tools play a crucial role in modern education by enhancing the learning process, promoting interactive understanding, and developing essential skills (Vascan, 2024). Previous studies has shown than virtual laboratories support both individual and collaborative learning environments thereby allowing students to actively participate in social communities. By incorporating virtual labs in place of traditional laboratories, educators can improve student engagement, retention, and transfer of learning across various scientific disciplines (Vascan, 2024).

Teacher Training and Integrated Science Education

Previous studies have shown that a large percentage secondary science teachers lack the ability to develop integrated science practical lessons, as a result of their specialized backgrounds in individual science disciplines (Rubini et al., 2018). To address this, various approaches have been explored, including Laboratory-based training courses for preservice teachers (Valls-Bautista et al., 2021), professional development programs focusing on practical syllabus, pedagogical content knowledge, and STEM instructional materials (Lertdechapat & Faikhanta, 2021).

Related Work

Tuysuz (2010) used quasi-experimental designs to prove that VLs were capable of overcoming time, cost, and safety limitations in traditional chemistry laboratories, but in the case of the study was confined to one subject. Likewise, Dela Cruz and Mendoza (2018) addressed the issue of inadequate facilities and equipment of engineering courses by creating an immersive Virtual Reality (VR) setting, which is limited by the high cost of the special equipment and the simplicity of the experiment introduced. More recently, the problem of resources to serve large student populations in Nankai University was solved by Zhang and Liu (2023) through the high-scale implementation of a platform of 41 simulation projects, and this method has difficulties in ensuring uniformity among various projects. The other problem as emphasized in the past research is the pedagogical and design dilemma of VL implementation. In cases Coutinho et al. (2023) found the absence of a systematic process of development, the author suggested a conceptual model that would join backward design and software engineering, but this methodology needs to be empirically tested. Miyamoto et al. (2019) were interested in enhancing the students in their background knowledge on the basic biology procedures using 3D interactive animation, but had to be constrained by the fact that the virtual setting was based on errors in the underlying lab manuals. Reginald (2023) applied a systematic review to evaluate the influences of VLs on self-regulated learning (SRL) in the COVID-19 transition, but the weaknesses included the fact that the conclusions were drawn by secondary data. Within the framework of collaborative learning, Kurtz et al. (2025) identifies the necessity of enhanced integration of learning analytics, while Elmoazen et al. (2023) emphasized and identified the fact that at present, the situation is disjointed and standardized protocols are missing, which can be used to track the progress of students on different platforms.

Methodology

The virtual lab was developed as a web-based program based on Flask (python 3.14). The logic of chemical reactions and user session management were implemented with the help of the backend, while the frontend uses HTML5, CSS3, and JavaScript to display the interactive interface. Application architecture is a Model-View-Controller (MVC) type, which is scalable and easy to modify various modules of chemicals. In order to measure the efficacy of the virtual lab, quasi-experimental design was used involving a sample of Nigeria Certificate in Education Students in the department of integrated science Education. The respondents were separated into an Experimental Group (Virtual Lab) and Control Group (Traditional).

Design, Development and Evaluation of ... Adediran, T. D. & Oke, A. A. (2025)

Design and Development

Phase 2: Design and Development

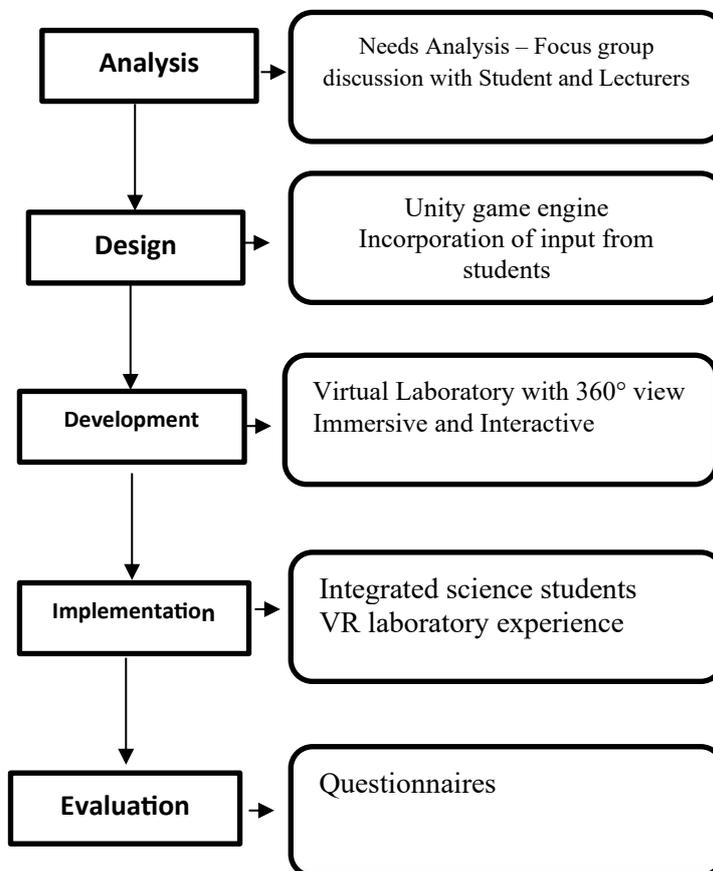


Figure 1: Phases of the Virtual laboratory for NCE Integrated Science Student

This stage consists of the design and the development of the virtual laboratory through iterative prototyping. The scalability and the flexibility was ensured in a modular architecture. The logic was written in Python programming language and web interface written in JavaScript scripting language and HTML and CSS. The developmental tool was utilized as the Unity to simulate on 3D and WebGL to make it compatible on the browser. The characteristics of the Virtual Laboratory were Interactive Simulations where core experiments in the teacher training programme on integrated science subjects are physics, chemistry, as well as biology, though the emphasis in the initial phase of the implementation activity was the use inclusion of certain Chemistry laboratory practicals as contained in the National Commission of Colleges of Education minimum standard. A completed web application containing six interactive chemistry experiments (Acid-Base Titration, Stoichiometric Calculations, Buffer Solutions, Precipitation Reactions, Redox Reactions, Gas Laws) as shown on table 1 with real time parameter manipulation, live visualization of data represented on Figure 3, 4 and 5.

Table 1

Summary of Implemented Virtual Lab Experiments, Learning Objectives, and Key Features

Experiment	Learning Objectives	Key Features
Acid-Base Titration	Understand titration principles and calculate molarity	Real-time pH monitoring; indicator color changes
Stoichiometric Calculations	Apply stoichiometry to chemical reactions	Molar ratio visualization; limiting reagent identification
Buffer Solutions	Understand buffer capacity and pH	pH monitoring; buffer component adjustment

Design, Development and Evaluation of ... Adediran, T. D. & Oke, A. A. (2025)

Precipitation Reactions	Predict and observe precipitation reactions	Ionic equation visualization; solubility rules
Redox Reactions	Understand electron transfer processes	Oxidation state visualization; half-reaction balancing
Gas Laws	Apply the ideal gas law	Pressure–volume–temperature relationships

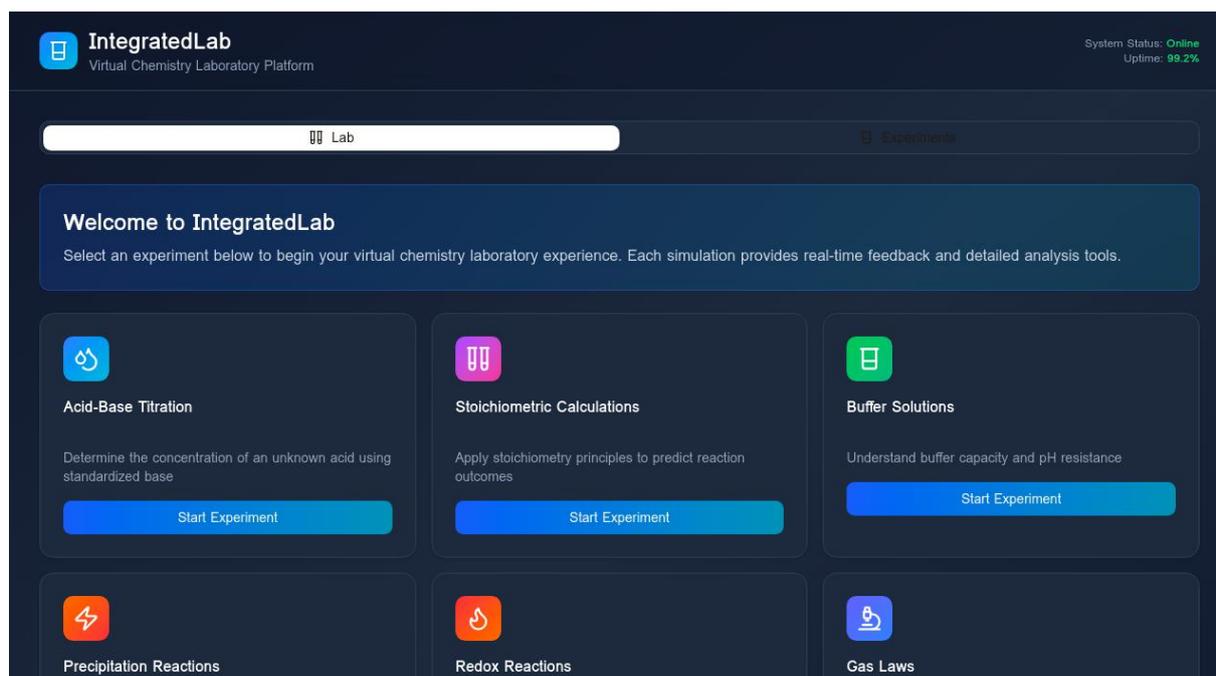


Figure 2. Flask application interface for Integrated Laboratory Interface simulation.

Evaluation of Virtual Laboratory

Study Area/Site/Subjects:

The evaluation was conducted at selected Colleges of Education in Osun state, Nigeria. Using purposive sampling, one federal owned college (Federal College of Education, Iwo), one state-owned college (Osun State College of Education, Ila-Orangun) and a private college of education (Assanusiyah College of Education Ode-Omu) were selected for the evaluation of the developed virtual laboratory. The primary subjects of the study were NCE students enrolled in the Integrated Science Education programs. The developed Virtual Laboratory was tested with a group of student-teachers who are currently enrolled in integrated science. A total sample size of 120 students was selected using random sampling techniques from the chosen institutions. The students were divided into two groups: a Experimental Group (N=60) and a Control Group (N=60).

Data Collection:

Data was collected using a quantitative method with a questionnaire instrument. Additionally, a set of tests (Pre-Test and Post-Test) were administered before and after the use of the VL to assess changes in students' practical skills, scientific knowledge, and teaching competency.

Data Analysis:

Quantitative data was analyzed using statistical methods to compare pre- and post-test results specifically, T-tests to compare pre-test and post-test scores.

Design, Development and Evaluation of ... Adediran, T. D. & Oke, A. A. (2025)

Presentation of Results

The evaluation of the Virtual Laboratory (VL) showed significant quantitative and qualitative data. This section presents the findings from the pre- and post-test assessments, usability surveys, and classroom observations, providing a comprehensive picture of the VL's impact on student-teachers.

Student Learning and Competency Outcomes

In order to determine the effect of the VL on the learning of the students, pre-test and post-test were conducted in 120 student-teachers. The different tests were intended to test three major areas: Practical Skills Knowledge, Scientific Conceptual Knowledge and Teaching Competency. Paired-samples t-test, showed statistically significant increase in the overall scores after the four weeks of intervention period. The means became 85.30 (SD = 7.50) against 64.50 (SD = 8.20) in the post-test and pre-test respectively, $t(149) = 21.8, p < .001$. This difference is significant (mean difference = 20.8 percentage points) and demonstrates a significant and positive change in the performance of students. In order to get more insight, the scores were segregated by the area of competency. As Table 2 indicates, there were considerable improvements in all the three areas. The greatest improvement was observed in Practical Skills Knowledge where it improved by 24.5 percentage points.

Table 2

Descriptive Statistics for Pre-Test and Post-Test Scores by Competency Area (N=120)

Competency Area	Test	Mean (%)	Std. Deviation	Mean Difference (%)
Practical Skills Knowledge	Pre-Test	61.2	9.5	24.5
	Post-Test	85.7	7.8	
Scientific Conceptual Knowledge	Pre-Test	68.1	8.9	18.9
	Post-Test	87.0	7.1	
Teaching Competency	Pre-Test	64.2	9.1	19.0
	Post-Test	83.2	8.0	
Overall Score	Pre-Test	64.5	8.2	20.8
	Post-Test	85.3	7.5	

Figure 3: Home page with experiment selection and educational overview

Design, Development and Evaluation of ... Adediran, T. D. & Oke, A. A. (2025)

User Experience and Perceived Effectiveness

The mean System Usability Scale (SUS) score was 88.5 (SD = 6.2), indicating an Excellent level of usability. Feedback from the questionnaire, as shown in Table 3, was positive, with 96.0% of student teachers feeling more confident in their teaching abilities after using the platform.

Table 3

Student-Teacher Feedback on the Virtual Laboratory (N=120)

Survey Item	Strongly Agree (%)	Agree (%)	Neutral (%)	Disagree (%)	Strongly Disagree (%)
The VL was easy to use and navigate.	72.0	24.0	4.0	0.0	0.0
The VL was an effective tool for my learning.	68.0	26.7	5.3	0.0	0.0
I feel more confident in my teaching abilities.	70.7	25.3	4.0	0.0	0.0
The accessibility of the VL was beneficial.	81.3	16.7	2.0	0.0	0.0

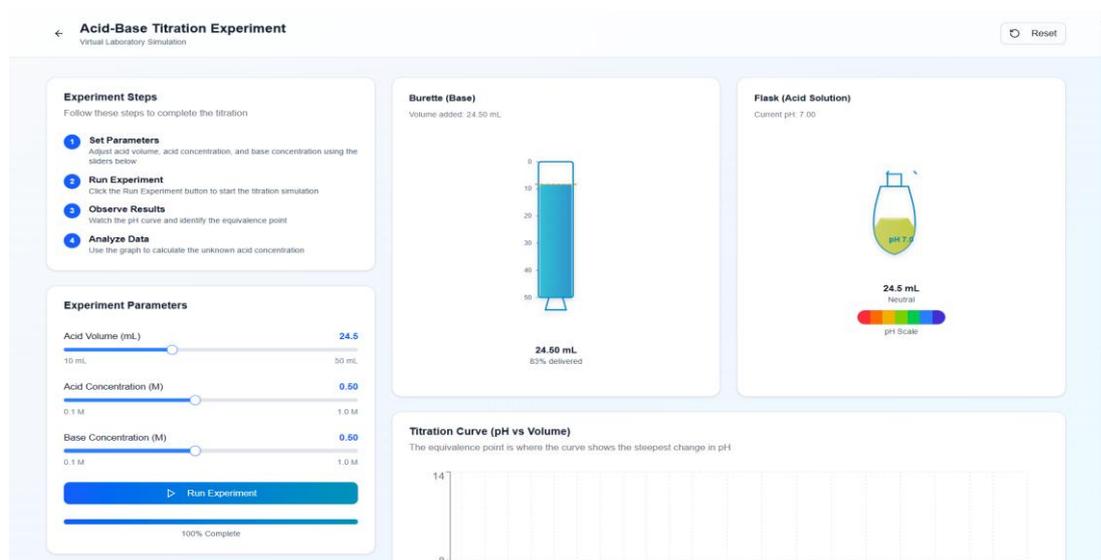


Figure 4: Animated burette visualization showing liquid delivery

Design, Development and Evaluation of ... Adediran, T. D. & Oke, A. A. (2025)

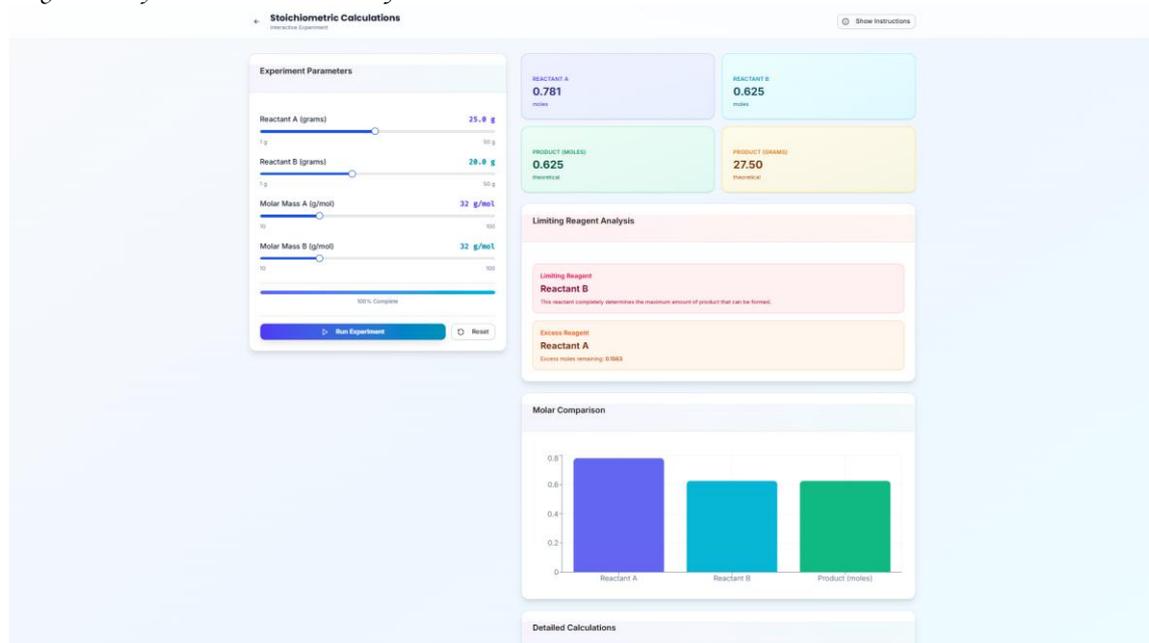


Figure 5: Simulated Accurate pH curve generation using stoichiometric calculations

Discussion of Findings

The results indicate that the Virtual Laboratory is a very productive tool to use in training integrated student-teachers. The dramatic rise in test scores is consistent with the studies that VLS have the potential to generate learning outcomes that are similar or even better than those generated by conventional labs. Practical Skills Knowledge was the most improved and this implies that the risk-free environment of the VL is the best place to learn the logic behind the procedure. The Scientific Conceptual Knowledge and Teaching Competency gains can be attributed to the fact that the VL brings abstract concepts to life and that it can be easily integrated into the teaching practice. The high usability measure proves that the user-centered design was effective and reduced the cognitive load and enabled learners to concentrate on the content. The results indicate that the VL is a potent complement to the conventional labs, which fosters equity to offer high-quality experiences to every learner and aid in the creation of modern educators who can effectively operate with technology. A randomized controlled trial should be used in future studies to compare the VL with the traditional instruction per se and carry longitudinal studies to determine long-term knowledge retention.

Conclusion

This research paper can prove that a web-based Virtual Laboratory (VL) has a remarkable positive influence on the training of pre-service teachers of integrated science. The study aimed at assessing how effective the VL is in practical skills, scientific knowledge, and teaching competence development. The results verify that VL is an effective educational instrument and, the results obtained are significant and statistically significant in terms of improvement of students-teacher performance. The main conclusions drawn from this study are:

1. The Virtual Laboratory has significant accelerating effects on learning: The intervention led to increasing assessment scores on overall, with significant improvement of knowledge in practical skills, conceptual knowledge, and teaching competency. This proves that a properly drawn virtual environment may be an effective means of teaching.
2. A positive user experience is critical to success: The high usability rating (SUS M = 88.5) and the vast majority of positive user experience feedbacks confirm the need to focus on user-driven design. The user-friendly and intuitive design of the VL also enabled student-teachers to concentrate on learning and not using a complicated tool.
3. The VL fosters confidence and innovative teaching: Qualitative data showed the importance of the risk-free environment of the VL, which enabled student-teachers to rehearse and learn complex procedures and developed more confidence. Such confidence, in its turn, carried into more creative and efficient pedagogical activities in their practicums as teachers.



Design, Development and Evaluation of ... Adediran, T. D. & Oke, A. A. (2025)

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Design, Development and Evaluation of ... Adediran, T. D. & Oke, A. A. (2025)

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