BRIDGING THE GAP WITH TECHNOLOGY: A COMPARATIVE STUDY OF VIRTUAL LABS AND SIMULATIONS ON STUDENTS' ACADEMIC ACHIEVEMENT IN SECONDARY SCHOOL BIOLOGY

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Abstract

This study compared the effectiveness of virtual laboratory and simulation instructional approaches on secondary school students' academic achievement in Biology in Anambra State, Nigeria, and examined the influence of gender on learning outcomes. A quasi-experimental, non-randomized pre-test post-test non-equivalent group design was adopted. A sample of 98 SS1 Biology students (40 males; 58 females) drawn from co-educational secondary schools in Nnewi Education Zone participated in the study. Data were collected using the Biology Achievement Test (BAT), a 40-item multiple-choice instrument adapted from past West African Examinations Council questions, with a reliability coefficient of 0.88 obtained via the Kuder-Richardson Formula 20. Descriptive statistics (mean and standard deviation) were used to answer the research questions, whilst Analysis of Covariance (ANCOVA), with pre-test scores as covariate, was used to test the hypotheses at a 0.05 level of significance. Findings revealed that students in the virtual laboratory group recorded a mean achievement gain of 43.00, marginally higher than the 41.80 recorded by the simulation group, though the difference was not statistically significant ($F = 0.608$, $p = 0.437$). Gender had no significant influence on achievement in either group, and there was no significant interaction effect of teaching method and gender on students' achievement in Biology. Both instructional approaches are therefore comparably effective and gender-neutral tools for enhancing Biology learning outcomes at the secondary school level. It was recommended that Biology teachers integrate virtual laboratory and simulation strategies into their instruction, and that government and school administrators provide the technological infrastructure necessary to support their sustained implementation.

Keywords: virtual laboratory, simulation, Biology achievement, gender, secondary school, quasi-experimental

Introduction

The teaching and learning of Biology at the secondary school level has long relied on well-equipped laboratories to provide students with hands-on practical experiences, through which learners develop critical scientific skills including observation, measurement, and inquiry-based reasoning (Chala, 2019). However, the reality in many Nigerian secondary schools falls significantly short of this ideal. Fasoye (2023) observed that numerous schools operate without functional laboratories, while those with facilities often lack adequate equipment, reagents, and specimens. Patrick-Okwoli (2024) further asserted that overcrowded classrooms and safety concerns around biological specimens have pushed many Biology teachers towards theoretical instruction as the only practicable option, leaving students with little or no exposure to the hands-on investigative experiences that Biology education demands.

In response, educators and researchers have increasingly turned to technology-driven alternatives, among the most prominent of which are virtual laboratories and simulations (Yusuf *et al.,* 2025). Although frequently used interchangeably in educational discourse, these represent distinct pedagogical tools. A virtual laboratory is a computer-based interactive environment that replicates the look, feel, and functionality of a real physical laboratory, enabling students to perform experiments by manipulating virtual equipment, collecting data, and engaging with procedural scientific processes without associated costs, space requirements, or safety risks (Carroll *et al.,* 2025; Griffin *et al.,* 2025). A simulation, by contrast, is a computer program that models a real or theoretical system, allowing learners to explore relationships between variables by altering input parameters and observing corresponding effects, with emphasis on underlying concepts and principles rather than procedural replication (Reen *et al.,* 2025; Fiedler *et al.,* 2026). Zacharia (2015) captured this distinction succinctly, stating that virtual laboratories emphasize the doing of science, while simulations emphasize the thinking behind science, and both are essential for scientific literacy.

Academic achievement, as a widely recognized indicator of students' educational progress, reflects the knowledge and skills acquired through formal education and is shaped by instructional methods, learning resources, and prior knowledge (Steinmayr *et al.,* 2024; Chengere *et al.,* 2025). Gender differences in achievement remain a significant concern in science education, with evidence from the Nigerian setting remaining inconsistent. While Gaisey *et al.* (2024) reported male superiority in Biology achievement, Wrigley-Asante *et al.* (2023) found no significant gender differences. Thomas (2023) attributed such disparities to societal

expectations, instructional methods, and access to learning resources, while Young (2025) contended that technology-enhanced environments can provide more equitable learning opportunities for both genders.

The urgency of exploring technology-mediated instructional strategies was amplified by the COVID-19 pandemic, which forced schools to suspend laboratory sessions and transition to online learning, prompting Biology instructors to seek viable virtual alternatives (Johnson & Afolabi, 2024; Tubookoseimie & Onyedibia, 2023). More recently, the Federal Ministry of Education directed the West African Examinations Council (WAEC) and the National Examinations Council (NECO) to fully migrate all components of the Senior School Certificate Examination, including practicals, to Computer-Based Testing by 2026 (Anyanwu, 2025; Moses, 2025), yet many Biology students in Nigerian secondary schools remain largely unprepared for this transition, having had little or no structured exposure to technology-enhanced learning environments.

Despite the growing interest in virtual laboratories and simulations, empirical evidence comparing their relative effectiveness in enhancing students' academic achievement in Biology, particularly within the Nigerian setting, remains limited (Acheampong *et al.,* 2026; Isaac & Okoli, 2025; Olojo *et al.,* 2024). Therefore, this study sought to bridge this gap by comparing the effectiveness of virtual laboratories and simulation instructional approaches on secondary school students' academic achievement in Biology, whilst also examining the influence of gender on learning outcomes, with the intention of providing educators, curriculum developers, and policymakers with evidence to guide informed decisions regarding technology integration in Nigerian secondary schools.

Research Questions

The following research questions guided the study;

1. What are the differences in the mean achievement scores of students taught Biology using virtual laboratory and simulation instructional approach?
2. What is the influence of virtual laboratory and simulation instructional approach on the mean achievement scores of male and female students taught Biology?

Hypotheses

The following hypotheses were tested at a 0.05 level of significance.

1. There is no significant difference in the mean achievement scores of students taught Biology using virtual laboratory and simulation instructional approach.

2. There is no significant influence of virtual laboratory and simulation instructional approach on the mean achievement scores of male and female students taught Biology.
3. There is no interaction effect of teaching methods and gender on the achievement scores of students in Biology.

Method

The study adopted quasi-experimental design, specifically, a non-randomized, pre-test, post-test, non-equivalent group design. A quasi-experimental design is a type of empirical investigation that resembles a true experiment but lacks full randomization of participants into treatment groups, making it particularly suitable for educational settings where intact classes must be preserved (Creswell & Creswell, 2018). This design was considered appropriate given that complete randomization of participants into groups was not feasible, necessitating the use of intact classes. The design enabled systematic comparison of two technology-mediated instructional approaches, virtual laboratory and simulation-based instruction, by assessing students' Biology achievement before and after treatment, whilst controlling for pre-existing differences between groups through the use of pre-test scores as a covariate.

The study was conducted in Nnewi Education Zone, one of six education Zones in Anambra State, comprising four Local Government Areas: Ekwusigo, Ihiala, Nnewi North, and Nnewi South. The Zone hosts 49 government-owned secondary schools and is notable for its cultural diversity, economic dynamism, and ongoing educational reforms, making it a representative setting for investigating technology-mediated instruction in Nigerian secondary education. The target population comprised 3,013 SS1 Biology students (1,212 males; 1,801 females) enrolled in these schools.

A sample of 98 SS1 Biology students (40 males; 58 females) was drawn from 34 co-educational secondary schools in the Zone using stratified and simple random sampling techniques. Stratified sampling ensured proportional representation by gender, whilst simple random sampling was employed in selecting participating schools and assigning groups.

Data were collected using the Biology Achievement Test (BAT), a 40-item multiple-choice instrument with four options (A–D) adapted from past West African Examinations Council questions. Items reflected Biology concepts taught during the study period, specifically microorganisms. Each correct response was awarded 2.5 marks, whilst incorrect or unanswered items received zero, yielding a maximum

score of 100. The BAT served as both pre-test and post-test, with items reshuffled between administrations to minimise order effects. Content and face validity were established through review by three experts.

The reliability of the BAT was determined using the Kudder-Richardson-Formula 20 ($K\text{-}R_{20}$), appropriate for dichotomously scored items with varying difficulty levels. A pilot administration to 20 SS1 Biology students at Community Secondary School, Ugwuoba, Enugu State, who were not part of the main study, yielded a reliability coefficient of 0.88, indicating high internal consistency.

The experiment was implemented in four stages. First, Biology teachers from the sampled schools serving as research assistants were trained over four days on the respective instructional approaches. The teacher assigned to Experimental Group 1 was trained on virtual laboratory-based instruction, whilst the one assigned to Experimental Group 2 was trained on simulation-based instruction. Detailed lesson plans, demonstrations, and supervised practice sessions were provided to ensure fidelity of implementation.

Second, a pre-test was administered to students in both groups prior to treatment to establish baseline knowledge of microorganisms. No feedback was provided following the pre-test. Third, both groups received Biology instruction over four weeks, with Experimental Group 1 taught using virtual laboratory method and Experimental Group 2 taught using simulation-based instruction. Fourth, in the fifth week, the reshuffled BAT was administered as a post-test to assess post-treatment achievement. This structured procedure ensured consistency across groups and minimized threats to internal validity.

Pre-test and post-test scores were collected from both experimental groups by research assistants and recorded for analysis. Descriptive statistics, specifically mean and standard deviation, were used to address the research questions. The hypotheses were tested at a 0.05 level of significance using Analysis of Covariance (ANCOVA), with pre-test scores serving as the covariate to control for initial group differences. The null hypothesis was rejected when the probability value was equal to or less than 0.05 ($p \leq 0.05$) and retained when $p > 0.05$.

Results

Research Question 1: What are the differences in the mean achievement scores of students taught Biology using virtual laboratory and simulation instructional approach?

Table 1: **Difference in the mean achievement scores of students taught Biology using virtual laboratory and simulation instructional approach**

Source of variation	N	Prete Mean	Posttest SD	Posttest Mean	Gained SD	Gained Mean
Virtual Laboratory	48	32.33	16.72	75.33	15.31	43.00
Simulation Approach	50	32.18	16.06	73.98	16.27	41.80
Mean Difference		0.37		1.35		1.20

Table 1 reveals that students in the virtual laboratory group recorded a pretest mean achievement score of 32.33 (SD = 16.72), which improved to 75.33 (SD = 15.31) at posttest, yielding a mean gain of 43.00. Similarly, students in the simulation group recorded a pretest mean of 32.18 (SD = 16.06), which improved to 73.98 (SD = 16.27) at posttest, yielding a mean gain of 41.80. The mean difference in achievement gain between both groups was 1.20, marginally favouring the virtual laboratory group. Both groups demonstrated substantial improvement from pretest to posttest;The mean difference in achievement gain between both groups was 1.20, marginally favouring the virtual laboratory group. Both groups demonstrated substantial improvement from pretest to posttest; however, the virtual laboratory approach appeared slightly more effective in enhancing students' understanding of Biology than the simulation-based approach.

Research Question 2: What is the influence of virtual laboratory and simulation instructional approach on the mean achievement scores of male and female students taught Biology?

Table 2: Influence of virtual laboratory and simulation instructional approachon the mean achievement scores of male and female students taught Biology

Treatment groups	N	Gender	Pre-test Mean	SD	Post-test Mean	SD	Gained Mean
Virtual Laboratory	28	Male	31.36	15.61	74.98	15.68	43.62
	20	Female	32.46	16.58	75.08	14.52	42.62
Simulation Approach	19	Male	31.58	16.09	73.43	14.94	41.85
	31	Female	32.76	15.96	74.72	16.01	41.96

Table 2 reveals that both male and female students in the virtual laboratory and simulation groups recorded substantial improvements in posttest mean

achievement scores relative to their pretest scores. In the virtual laboratory group, male students recorded a mean gain of 43.62, marginally higher than the mean gain of 42.62 recorded by their female counterparts. In the simulation group, female students recorded a slightly higher mean gain of 41.96 compared to 41.85 recorded by male students. Across both instructional approaches, the differences in mean achievement gains between male and female students were negligible, suggesting that neither approach conferred a pronounced gender-based advantage. Notably, both male and female students in the virtual laboratory group outperformed their counterparts in the simulation group, further corroborating the marginal superiority of virtual laboratory instruction.

Test of Null Hypothesis

Hypothesis 1: There is no significant difference in the mean achievement scores of students taught Biology using virtual laboratory and simulation instructional approach.

Table 3: Analysis of Covariance (ANCOVA) test of significant difference in the mean achievement scores of students taught Biology using virtual laboratory and simulation instructional approach.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Parial. Eta Square
Corrected Model	984.806	2	61.602	4.511	.025	.057
Intercept	8354.903	1	354.90	16. 666	.000	.664
Pretest	2683.149	1	683.149	7.312	.009	.053
Methods	93.534	1	6.767	.608	.437	.005
Error	3623.518	96	4.05			
Total	36432.000	98				
Corrected Total	4068.324	97				

a. R Squared = .057 (Adjusted R Squared = .042) P = 0.437>0.05

Table 3 shows that there is no significant difference in the mean achievement scores of students taught Biology using virtual laboratory and those taught with simulation instructional approach, F = 0.608, P = 0.437>0.05. Therefore, the null hypothesis is retained which means that there is no significant difference in the mean achievement scores of students taught Biology using virtual laboratory and those taught with simulation instructional approach.

Hypothesis 2: There is no significant influence of virtual laboratory and simulation instructional approach on the mean achievement scores of male and female students taught Biology.

Table 4:Analysis of Covariance (ANCOVA) test of significant influence of virtual laboratory and simulation instructional approach on the mean achievement scores of male and female students taught Biology

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Parial. Eta Square
Corrected Model	5875.524	2	2937.762	1.858	.000	.057
Intercept	17631.003	1	17631.003	131.183	.000	.662
Pretest	5868.087	1	5868.087	43.661	.000	.052
Group	71.384	1	71.384	.531	.470	.005
Gender	.891	1	.891	.009		.000
Group * Gender	6.187	1	6.187	.063		.001
Error	6316.796	96	97.883			
Total	247216.000	98				
Corrected Total	12192.320	97				

a. R Squared = .057 (Adjusted R Squared = .027), P= 0.802> 0.05

Table 4 shows that there is no significant difference between the mean achievement scores of male and female students exposed to virtual laboratory and simulation instructional approach, F= 0.063, P>0.05. Therefore, the null hypothesis is retained which implies that male and female students taught Biology using virtual laboratory and those taught with simulation instructional approach achieved equally.

Hypothesis 3: There is no interaction effect of teaching methods and gender on the achievement scores of students in Biology.

Table 5: ANCOVA test of interaction effect of teaching methods and gender on the achievement of students in Biology

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	4575.545	4	**1143.886**	18.194	.000	.439
Intercept	27841.34	1	27841.340	442.825	.000	.662
Pretest	868.087	1	868.087	13.807	.000	.083

Group	43.345	1	43.345	0.689	**.408**	.006
Gender	7.913	1	7.913	17.564	.724	.001
Group * Gender	8.456	1	8.456	0.134	.715	.052
Error	5847.109	93	**62.872**			
Total	856216.056	98				
Corrected Total	10422.654	97				

a. R Squared = .439 (Adjusted R Squared = .394)

Table 5 shows that there is no main interaction effect of teaching methods and gender on the achievement scores of the students Biology, F (1, 93) = 0.134, P = 0.715 > 0.05. Therefore, the null hypothesis is not rejected. Thus, there is no interaction effect of teaching strategies and gender on the achievement scores of students in Biology. This means that the significant effect on students' achievement was caused by the effect of the teaching methods during the experiment. The interaction plot is shown in Figure 1.

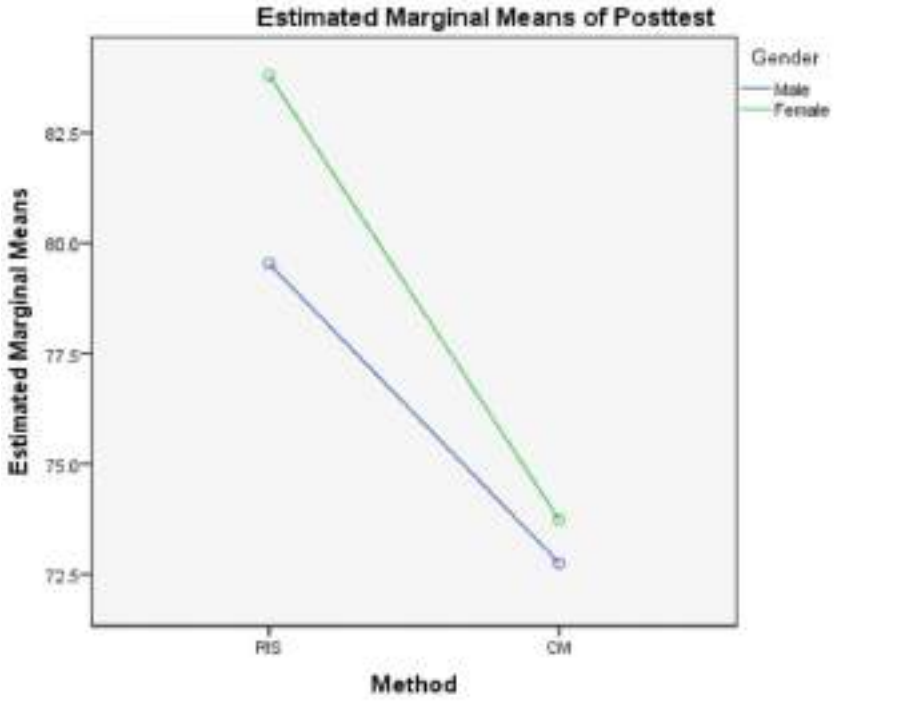

Figure 1: Plot of interaction effect of teaching methods and gender on students' achievement in Biology

The plot of interaction effect of teaching methods and gender on students' achievement in Biology is not significant and ordinal. This shows that effect of the instructional approaches did not change when gender was put into consideration. Thus, the methods are not gender biased with respect to achievement.

Discussion of Findings

The findings of the study showed that students exposed to virtual laboratory performed slightly better than those exposed to the simulation instructional approach, although the difference was not statistically significant. This confirms that both virtual laboratory and simulation instructional approaches are learner-centred and capable of making a remarkable impact on instructional practices. The higher achievement recorded by both methods may be attributed to the active interaction and participation of all students in the treatment process. This result aligns with the findings of Olojo *et al.* (2024), Isaac and Okoli (2025), Lawal *et al.* (2025), Yusuf *et al.* (2025), and Acheampong *et al.* (2026), who, in their various studies, reported that students taught using virtual laboratories and simulation instructional approaches achieved better academically in sciences. The marginal superiority of virtual laboratory instruction observed in this study is further corroborated by Carroll *et al.* (2025), who demonstrated the effectiveness of virtual laboratory simulations in enhancing students' academic understanding of scientific concepts, and by Xu *et al.* (2025), whose large-scale randomized controlled trial in medical microbiology laboratory education confirmed the significant academic benefits of web-based simulation for students. Wörner *et al.* (2022) similarly reported, in a systematic review of real and virtual experiments in science education, that both approaches yield substantial learning gains, with neither consistently outperforming the other at a statistically significant level. Griffin *et al.* (2025) further observed that virtual laboratories complement traditional instructional methods effectively, supporting students' understanding even when physical laboratory access is limited.

Additionally, it was discovered that both virtual laboratories and simulation instructional approaches are non-gender-discriminatory teaching methods, indicating that gender is not a determinant of students' academic achievement. This finding is consistent with the findings of Egwu and Okigbo (2021), Thomas (2023), and Dobrokhotov *et al.* (2025), who found that when both male and female students are given equal opportunities and allowed to actively participate in the learning process, they perform equally. This finding is also corroborated by Gaisey *et al.* (2024), who reported that learning environments influenced academic performance

across genders without producing significant gender-based disparities. This contradicts the finding of Wrigley-Asante *et al.* (2023), who reported a significant difference between male and female students' academic achievement in STEM subjects, suggesting that gender-based performance gaps may be more pronounced in certain institutional or disciplinary contexts than in technology-enhanced, learner-centred instructional settings such as those investigated in the present study.

Furthermore, it was revealed that there was no interaction effect of teaching methods and gender on the achievement scores of students in Biology. This implies that the effect of the instructional approaches did not change when gender was considered, indicating that the methods are not gender-biased with respect to achievement. This finding is in line with the findings of Lawal *et al.* (2025), who reported that blended STEM instruction using virtual labs and simulations was not gender-biased concerning academic achievement in Biology education, and with Dobrokhotov *et al.* (2025), whose bibliometric study on gender in ICT-integrated STEM education found no evidence that technology-enhanced instructional approaches systematically disadvantage either gender. The implications of these findings emphasize the potential of virtual laboratory and simulation instructional approaches to serve as equitable, inclusive pedagogical tools capable of enhancing academic achievement in Biology irrespective of students' gender.

Conclusion

The findings of this study conclude that both virtual laboratory and simulation instructional approaches are effective in facilitating students' academic achievement in understanding concepts related to microorganisms in Biology. Although students taught using the virtual laboratory approach recorded a marginally higher mean achievement gain than those taught using the simulation approach, the difference was not statistically significant, indicating that both methods are comparably effective in enhancing Biology learning outcomes at the secondary school level. Furthermore, the study established that gender had no significant influence on the academic achievement of students exposed to either instructional approach, and that there was no interaction effect of teaching method and gender on students' achievement in Biology. This suggests that both virtual laboratory and simulation instructional approaches are learner-centered, non-gender-discriminatory teaching methods that provide equal learning opportunities for all students regardless of their gender, and that their adoption in the teaching and learning of Biology holds considerable promise for improving students' academic achievement in Nigerian secondary schools and beyond.

Recommendations

Based on the findings of this study, the following recommendations were made:

1. Virtual laboratory and simulation approaches should be integrated into the Biology curriculum by curriculum developers and Biology teachers to provide diverse and engaging learning experiences for students.
2. Government should provide adequate funding and policy support for the acquisition of technological infrastructure, including computers, software, and internet connectivity, in public secondary schools.
3. School administrators should invest in maintaining technological infrastructure to facilitate the effective implementation of these instructional approaches.
4. Teacher training programmes should equip pre-service and in-service science teachers with the necessary skills to utilize virtual laboratory and simulation strategies effectively.
5. Biology teachers should adopt both approaches in their instruction and ensure equal opportunities for active participation among male and female students.

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