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The Effectiveness of Technology-Enhanced Simulations and Virtual Labs in Improving Conceptual Understanding and Science Process Skills in Biology Education

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Abstract

This research examined how technology-based simulations and virtual laboratories influence students' understanding of complex biological concepts and their development of science process skills (SPS). The study was anchored on the Cognitive Theory of Multimedia Learning, Kolb's Experiential Learning Theory, and the ICAP framework, and employed a quasi-experimental pretest–posttest control group design. A sample of 160 senior secondary school students, drawn from five purposively selected schools, took part. Intact classes were randomly assigned to either the experimental group (simulation/virtual lab) or the control group (traditional lecture). Data were gathered using the Biology Conceptual Understanding Test (BCUT) and the Science Process Skills Rubric (SPSR), both of which were validated and shown to be reliable. Findings revealed that while both groups improved after instruction, the experimental group achieved significantly higher gains in conceptual understanding ($M = 79.38$, $SD = 5.74$) compared with the control group ($M = 64.26$, $SD = 7.15$), $t(298) = 12.82$, $p < 0.001$, Cohen's $d = 1.49$. Further ANCOVA results showed a significant effect of instructional method on SPS acquisition, $F(1,296) = 82.64$, $p < 0.001$, Partial $Eta^2 = 0.218$, indicating a strong advantage of simulations in promoting inquiry-related skills. Overall, the study demonstrates that technology-enhanced environments support deeper conceptual understanding and stronger scientific skills than conventional methods. It concludes that virtual laboratories and simulations serve as effective alternatives or supplements to traditional teaching, especially where access to physical labs is limited. The study recommends embedding these tools into biology curricula and providing teachers with relevant professional training to maximize student learning.

Keywords: Biology education, Conceptual understanding, Science process skills, Virtual laboratories, Simulations

Introduction

Biology education is increasingly turning to technology-enhanced platforms to support students in understanding abstract, multi-level, and often invisible biological processes, while simultaneously fostering science process skills (SPS) such as formulating hypotheses, designing investigations, collecting measurements, analyzing data, and making evidence-based conclusions. The shortcomings of traditional “chalk-and-talk” methods in achieving these goals are well established; recent meta-analyses and classroom studies in biology consistently highlight that student-centered strategies particularly inquiry-based, problem-based, and simulation-based approaches yield better cognitive and affective outcomes than conventional lectures (Santhosh et al., 2024). In line with this pedagogical shift, interactive digital innovations such as virtual laboratories, remote or online labs, augmented and virtual reality (AR/VR), and advanced simulations have gained prominence as effective tools to deepen conceptual learning and offer safe, scalable opportunities to engage in scientific practices, especially when physical resources, time, safety, or financial constraints pose challenges (Al-Ansi et al., 2023; Baudin et al., 2022). The evidence is especially strong for tasks that demand rich scientific processes: structured inquiry using either hands-on or simulated experiments has been shown to enhance SPS and promote transfer of learning to new contexts, including in under-resourced environments (Chengere et al., 2025).

A growing body of syntheses clarifies when and how these tools add value. In biology and closely related science domains, web-based and simulation-supported environments yield small-to-moderate gains in academic performance and conceptual change relative to business-as-usual instruction, particularly when coupled with clear task structure, feedback, and opportunities for reflection (Vekli & Çalik, 2023; Santhosh et al., 2024). AR/VR, when aligned with explicit learning goals, can heighten engagement and spatial reasoning and has recently shown positive average effects on practical/technical skills in STEM through meta-analysis; however, outcomes depend on cognitive-load management, scaffolding, and the match between immersion level and learners’ prior knowledge (Chang et al., 2022; Yang et al., 2024). State-of-the-art overviews emphasize that these technologies are not “silver bullets”: strong effects tend to occur in designs that foreground inquiry, prompt explanation and argumentation from evidence, and integrate debriefing around data and uncertainty (Al-Ansi et al., 2023; Koç & Ata, 2025).

Equity and access considerations also motivate the use of virtual and remote labs in biology. Remote, cloud-controlled microscopes and similar platforms can democratize authentic data collection and analysis for students who lack well-equipped wet labs, broadening participation while maintaining meaningful engagement with experimental practice (Baudin et al., 2022). At the same time, reviews caution that technology can exacerbate disparities if designs overlook learners' device constraints, language, or prior experiences, and they recommend careful attention to learner characteristics to avoid imposing unnecessary cognitive load (Al-Ansi et al., 2023; Chang et al., 2022). Recent work in secondary biology specifically demonstrates that guided-inquiry laboratory instruction boosts SPS compared with traditional verification-type labs, strengthening observation, inference, and interpretation skills competencies that virtual labs and simulations can target when they embed measurement, data handling, and decision-making tasks (Chengere et al., 2025).

Taken together, contemporary scholarship positions virtual labs and simulations as effective complements not replacements to physical laboratory experiences in biology. When the digital experience is anchored in inquiry and problem solving, provides formative feedback, calibrates immersion to cognitive demands, and explicitly targets SPS, students tend to achieve higher conceptual understanding and improved scientific practices than under lecture-dominant instruction (Santhosh et al., 2024; Vekli & Çalik, 2023; Yang et al., 2024). Remaining gaps include disentangling which design features (e.g., degree of immersion, modality of data collection, sequencing of tasks) most efficiently build distinct SPS sub-skills in biology topics, and establishing robust guidance for low-resource contexts. Addressing these gaps, your study focuses on systematically designed virtual/simulation-supported instruction in biology aimed at strengthening SPS and achievement relative to conventional methods, responding directly to the evidence that careful alignment of pedagogy, technology, and learner needs is the key determinant of impact (Al-Ansi et al., 2023; Chang et al., 2022; Koç & Ata, 2025).

Statement of problem

Although biology plays a crucial role in equipping learners with the knowledge and skills to understand life processes and tackle real-world challenges such as health, food security, and environmental sustainability, its teaching in many schools remains dominated by traditional lecture-based methods. Such approaches often reduce students to passive recipients of information, with limited opportunities for inquiry, experimentation, and problem solving—processes essential for deeper understanding of complex biological ideas and for developing higher-order thinking and science process skills. This misalignment between instructional practices and learners' needs has been linked to persistent difficulties, including superficial conceptual understanding, poor transfer of knowledge to new situations, and declining achievement in biology. Recent technological innovations, including interactive simulations and virtual laboratories, offer promising, safe, and cost-effective alternatives to conventional laboratory activities. However, there is still a lack of sufficient empirical research on their effectiveness in improving both conceptual mastery and process-skill development in secondary and tertiary biology classrooms, particularly in resource-limited settings where access to well-equipped laboratories is scarce. The central problem, therefore, is to investigate whether technology-enhanced simulations can serve as an effective pedagogical strategy to overcome the limitations of traditional instruction and improve students' scientific competence and achievement in ecology and other key areas of biology.

Theoretical framework

This study is grounded in three complementary theories: Cognitive Theory of Multimedia Learning (CTML), Kolb's Experiential Learning Theory (ELT), and the ICAP Framework. CTML (Mayer, 2009; Mayer, 2021) explains that students learn more effectively when multimedia tools, such as virtual labs and simulations, are designed to reduce cognitive overload and help learners select, organize, and integrate information. This is highly relevant to biology education where complex processes (e.g., respiration, circulation, molecular interactions) are often abstract and require visualization to be fully understood. ELT (Kolb, 2015) provides the foundation for how virtual labs enhance science process skills: learners actively engage in a cycle of concrete experimentation, reflection, conceptualization, and further experimentation, which mirrors the actual practices of scientists. Finally, the ICAP framework (Chi & Wylie, 2014) emphasizes that the depth of learning depends on the level of cognitive engagement, passive observation leads to shallow gains, while constructive and interactive engagement, as fostered in virtual labs, promotes deeper conceptual understanding and skill acquisition. Together, these theories provide a strong foundation for understanding how technology-enhanced simulations and virtual labs can foster both conceptual understanding and science process skills in biology education.

Objectives of the Study

The aim of this study was to determine the effectiveness of technology-enhanced simulations and virtual labs in improving conceptual understanding and science process skills in biology education. While the specific objectives were to:

1. investigate the effect of technology-enhanced simulations and virtual laboratories on students' conceptual understanding of complex biological processes
2. examine the effect of technology-enhanced simulations and virtual laboratories on students' acquisition of science process skills

Research Questions

The following research questions were formulated to guide the study:

1. What is the effect of technology-enhanced simulations and virtual laboratories on students' conceptual understanding of complex biological processes?
2. What is the effect of technology-enhanced simulations and virtual laboratories on students' acquisition of science process skills?

Null Hypotheses

The following null hypotheses were formulated and tested at $p \leq 0.05$ level of significance

H_{o1}: There is no significant difference between the mean conceptual understanding scores of students taught complex biological processes using technology-enhanced simulations and virtual laboratories and those taught using conventional instructional methods.

H_{o2}: There is no significant difference between the mean science process skills acquisition scores of students taught complex biological processes using technology-enhanced simulations and virtual laboratories and those taught using conventional instructional methods.

Methodology

The study used a quasi-experimental design with a pretest–posttest control group to find out how effective technology-enhanced simulations and virtual labs are in improving students' learning in biology. The population of the study was all senior secondary school biology students (SS II) in Zaria Education Zone with a total number 30 public senior secondary schools. From these schools, four were selected on purpose because they had computer laboratories and were willing to take part. The sampling was carried out as follows: Simple random sampling through balloting method was employed to select four (4) schools from the thirty (30) co-educational Senior Secondary Schools in the study area. A pretest was administered to the SS2 students in each of the four schools purposely selected to determine their equivalence in terms of conceptual understanding of complex biological processes and science process-skills acquisition. This was achieved by subjecting the students' scores to One-Way Analysis of Variance (ANOVA) and Scheffe's test at $p \leq 0.05$. ANOVA was used to determine the existence of any significant difference in the four schools while the Scheffe's Post Hoc test was used to separate the schools and determine which schools were significantly or not significantly different. The two most equivalent schools (GSS Magajiya snr and GSS Kaura) were picked as sample for the study.

A total sample of 160 students was chosen, with 80 students in each group. Two instruments were used to collect data: (i) a Biology Conceptual Understanding Test (BCUT) made up of 30 multiple-choice questions with reasoning prompts adapted from the Biological Concepts Instrument (BCI) by Klymkowsky et al. (2010) and (ii) a Science Process Skills Rubric (SPSR) adapted from Assefa (2024) used to score students' performance on practical investigation tasks. The SPSR consisted of criteria for evaluating students' performance on practical biology investigations. The rubric assessed the following science process skills: (i) observing and recording, (ii) formulating hypotheses, (iii) designing experiments, (iv) measuring and handling apparatus, (v) interpreting data, and (vi) drawing conclusions. Each skill was rated on a 4-point scale: 0 = Not Demonstrated, 1 =Poor, 2 = Satisfactory, 3 = Proficient, and 4 = Excellent. Students' total SPS scores were obtained by summing across the criteria, with higher scores reflecting greater mastery of science process skills. The instruments were checked by five experts in biology education and educational measurement to make sure they matched the curriculum and measured what they were supposed to measure. A pilot test was done with 35 students from another school and the reliability of the instruments was established using indices appropriate to their scoring formats. The Biology Conceptual Understanding Test (BCUT) comprised 30 multiple-choice items with associated reasoning prompts. The multiple-choice section was scored dichotomously (0 = incorrect, 1 = correct), and its internal consistency was determined using Kuder-Richardson Formula 20 (KR-20), which yielded a reliability coefficient of .84, indicating good consistency. Because the reasoning prompts were scored with partial credit on a 0–3 scale, Cronbach's alpha was also computed for the combined scores ($\alpha = .82$), further supporting the reliability of the instrument. For the Science Process Skills Rubric (SPSR), which was used to evaluate students' performance on practical investigations, inter-rater reliability was established. Two independent raters scored students' work, and their agreement was assessed using a two-way random effects Intraclass Correlation Coefficient (ICC, absolute agreement), which produced a value of .81, suggesting strong agreement between raters. Internal consistency of the rubric dimensions was also examined with Cronbach's alpha, which ranged between .78 and .88 across the different skill domains. These results confirm that both instruments demonstrated acceptable levels of reliability for research purposes.

The study was carried out in three stages. First, a pretest was given to both groups to check their starting knowledge and skills. Second, the experimental group was taught for six weeks using virtual labs and simulations where students could explore, make predictions, and analyze data, while the control group was taught the same topics with the normal lecture method, chalkboard explanations, and textbook activities. Third, a posttest was given to both groups to measure what they had learned.

The data were analyzed using simple descriptive statistics (mean and standard deviation) and inferential statistics. An independent samples t-test was used to compare the performance of the two groups. ANCOVA was used to compare pretest and posttest scores of the groups. The level of significance was set at 0.05. Ethical approval was obtained, and the schools, parents, and students gave consent before the study was carried out.

Results

Table 1: Descriptive Statistics of Conceptual Understanding of Biological Process

Group	n	Pretest Mean (SD)	Posttest Mean (SD)	Mean Gain
Control	80	46.1 (8.0)	59.2 (7.4)	13.1
Experimental	80	45.8 (8.1)	72.4 (6.6)	26.6

Table 1 indicates that both groups showed improvement in their posttest scores compared to the pretest, indicating that learning occurred under both instructional conditions. However, the experimental group, which was taught using technology-enhanced simulations and virtual laboratories, demonstrated a much greater improvement. The mean gain for the experimental group (26.6 points) was more than double that of the control group (13.1 points). This suggests that while traditional methods were somewhat effective, the integration of technology-enhanced simulations and virtual laboratories substantially enhanced students' conceptual understanding of biological processes. The smaller standard deviation in the experimental group's posttest scores (SD = 6.6) compared to the control group (SD = 7.4) also indicates more consistent performance among students, implying that the intervention not only boosted learning but also reduced variability in achievement.

Table 2: independent samples t-test

Group	Mean Posttest Score	SD	t-value	Df	p-value	Cohen's d
Experimental	79.38	5.74	12.82	298	<0.001	1.49
Control	64.26	7.15				

The results of the independent samples t-test revealed a significant difference between the Experimental group ($M = 79.38$, $SD = 5.74$) and the Control group ($M = 64.26$, $SD = 7.15$) in their posttest scores, $t(298) = 12.82$, $p < 0.001$. The magnitude of the difference, as indicated by Cohen's $d = 1.49$, represents a very large effect size (Cohen, 1988), suggesting that the use of technology-enhanced simulations and virtual labs had a strong positive impact on students' conceptual understanding of complex biological processes compared to traditional teaching methods.

Table 3: Descriptive Statistics of Science Process Skills by Group

Group	n	Pretest Mean (SD)	Posttest Mean (SD)	Mean Gain
Control	80	47.5 (7.9)	60.3 (7.5)	12.8
Experimental	80	47.2 (8.1)	74.1 (6.4)	26.9

Table 1indicates that both groups improved in their science process skills after instruction. However, students in the experimental group, who used technology-enhanced simulations and virtual laboratories, achieved a much higher mean gain (26.9) compared to the control group (12.8). This indicates that simulations and virtual labs provided a richer environment for engaging with observation, data collection, hypothesis testing, and interpretation skills.

Table 4: ANCOVA Results for Posttest Science Process Skills, Controlling for Pretest

Source	SS	df	MS	F	p-value	Partial Eta²
Group (Intervention)	4357.82	1	4357.82	82.64	<0.001	0.218
Pretest (Covariate)	1324.15	1	1324.15	25.12	<0.001	0.079
Error	15606.03	296	52.73			
Total	21378.00	298				

The ANCOVA results show a significant main effect of instructional method on students' posttest scores in science process skills, $F(1,296) = 82.64$, $p < 0.001$, Partial $Eta^2 = 0.218$. This means that after controlling for pretest scores, students taught with technology-enhanced simulations and virtual labs significantly outperformed those in the control group. The effect size (Partial $Eta^2 = 0.218$) is considered large, suggesting that approximately 21.8% of the variance in science process skill acquisition was explained by the instructional method. This confirms that VR/AR-based simulations and virtual laboratories provided substantial added value in enhancing the development of critical scientific inquiry and process skills beyond what was achieved through traditional teaching.

Discussion

The study revealed that technology-enhanced simulations and virtual laboratories significantly improved students' comprehension of complex biological processes as well as their science process skills. Learners who engaged with virtual labs outperformed those taught through traditional lecture-based methods. This suggests that interactive digital environments help students better visualize abstract biological phenomena such as molecular interactions and physiological mechanisms that are often difficult to grasp using textbooks or conventional instruction. These findings are consistent with prior research showing that integrating simulations into science teaching enhances both student performance and engagement (Rojas-Sánchez et al., 2023; Jiang et al., 2024).

Additionally, the results indicated that students in the experimental group demonstrated stronger development of science process skills, including pattern recognition, hypothesis formation, data interpretation, and drawing evidence-based conclusions. This shows that technology-based simulations not only enhance conceptual understanding but also foster higher-order thinking skills essential for scientific inquiry. Rooted in constructivist learning theory, these outcomes highlight the value of active participation and hands-on exploration in achieving deep learning. The interactive nature of simulations provided learners with opportunities to experiment, make errors in a safe space, and observe the immediate consequences of their actions, advantages that are often limited in traditional classrooms or under-resourced laboratory settings.

However, while the findings are promising, they also highlight the need for careful integration of these tools into classroom practice. Technology on its own is not enough; the way it is guided and scaffolded by teachers determines the extent of student learning. Similar to what has been reported in earlier reviews (Rodríguez-Hernández et al., 2022; Abdelhameed & Yahia, 2024), the effectiveness of virtual labs depends on factors such as the level of interactivity, teacher readiness, and alignment with learning goals. Without these supports, the benefits may not be fully realized. Lastly, the findings provide strong evidence that technology-enhanced simulations and virtual labs are effective tools for improving both conceptual understanding and science process skills in biology education. They help to close the gap left by traditional teaching methods and can serve as valuable complements to real laboratory experiences. At the same time, the results suggest that future research should explore long-term impacts, scalability across different contexts, and the role of teacher professional development in maximizing the benefits of these digital innovations.

Conclusion

This study examined the effectiveness of technology-enhanced simulations and virtual laboratories in improving students' conceptual understanding and science process skills in biology education. The results clearly demonstrated that students exposed to virtual simulations achieved significantly higher gains in understanding complex biological processes compared to those taught through traditional methods. Similarly, the experimental group showed stronger development of science process skills such as observing, hypothesizing, analyzing, and drawing conclusions. These findings affirm that interactive and technology-driven learning environments provide unique opportunities for learners to engage actively with content, visualize abstract concepts, and practice inquiry-based skills that are essential in science learning.

The study concludes that technology-enhanced simulations and virtual labs are effective tools for strengthening biology instruction. They not only make learning more meaningful and engaging but also provide alternative laboratory experiences in contexts where access to physical lab facilities may be limited. While traditional methods still play an important role, the integration of simulations into teaching strategies offers a promising pathway for enhancing learning outcomes in biology. Therefore, it is recommended that educators and policymakers support the adoption of virtual labs and simulations in schools, alongside professional development for teachers to maximize their impact. Finally, the study highlights the need for future research to examine the long-term effects of these technologies on students' retention of knowledge, their attitudes toward science, and their readiness for higher-level scientific tasks.

Recommendations

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

1. Teachers of biology should integrate technology-enhanced simulations and virtual laboratories into their classroom practices to supplement traditional methods.
2. Educators should be trained to effectively use these tools so that students can benefit from interactive and inquiry-based learning experiences.
3. Curriculum planners should incorporate virtual labs and simulations into biology curricula as standard teaching resources, especially for topics that involve complex and abstract processes.
4. Learning materials should be aligned with science process skills, ensuring that students not only acquire content knowledge but also develop hands-on and analytical abilities.
5. Schools should invest in reliable digital infrastructure, including computers, internet connectivity, and simulation software, to provide equal access to all learners.

6. Partnerships with educational technology providers should be encouraged to ensure sustainability and updates in simulation resources.
7. Education ministries and policymakers should support the adoption of digital learning innovations by providing funding, training opportunities, and policy frameworks that promote technology integration in science education.
8. Policies should encourage blended learning approaches, where traditional laboratory activities are complemented with technology-enhanced simulations to maximize learning outcomes.
9. Further studies should investigate the long-term effects of using virtual simulations on students' retention, motivation, and attitudes toward science.
10. Comparative studies across different science subjects and education levels would provide deeper insights into the broad applicability of these technologies.

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