International Journal of Science and Humanities Studies (IJSHS)
Vol 1 No. 1, 2026: 1-15
https://ojs.universityedu.org/index.php/ijshs

Assessing the impact of adaptive digital simulations on the conceptual understanding of molecular biology among graduate students in Delta State, Nigeria

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ARTICLE INFO

Keywords: *Adaptive digital simulations, Conceptual understanding, Molecular biology, Graduate students.*

Abstract

The study examined the nature and influence of adaptive digital simulations on the conceptual understanding of molecular biology in the hands of the graduate students of chosen public higher educational institutions in Delta. A quasi-experimental design was employed using the pretest, post-test results from 76 students who came from Molecular Biology and other postgraduate subjects. A design based on multistage sampling was chosen using the deliberate selection of university and department, and then randomly assigning the class to either the experimental group, which would have the adaptive digital simulations or the control group, which only had the traditional instruction. The data were collected using the Molecular Biology Conceptual Understanding Test (MBCUT), a package containing adaptive digital simulation (ADSP), Students' Perception Questionnaire (SPQ), and logs of engagement with the simulation platform. All these instruments were validated by experts with Cronbach's alpha > 0.70 to check reliability. The duration of the instructional intervention, employing adaptive digital simulations or traditional instruction, extended from 6 to 8 weeks following onboard post-test scores concerning conceptual understanding and the students' perceptions. Data collected were analyzed by paired sample t-tests, independent sample t-tests, ANCOVA, Pearson correlation, and regression analysis explaining the triadic relationship between conceptual understanding, engagement, and prior knowledge. It was observed that students in the experimental group receiving adaptive digital simulations significantly outperformed peers in the control group larvae of the traditional group in post-test scores ($t = 4.62$, $p < 0.05$) regardless of the levels of prior knowledge (ANCOVA, $F = 28.56$, $p < 0.05$, partial $\eta^2 = 0.28$). A few regressions had suggested that 18% of variance in post-tests was predicted by pre-socialization scores ($R^2 = 0.18$) as evidence of substantial involvement of prior knowledge, suggesting that cognition gained had a lot to do with the simulation intervention. Furthermore, students' engagement with the simulations was positively correlated with high scores on the post-test ($r = 0.62$, $p < 0.05$), drawing attention to the importance of active participation in technology-mediated teaching. From the results obtained, the study concluded that adaptive digital simulations can significantly lend to the toolkits of Nigerian higher education as enhancers of conceptual understanding in molecular biology through providing active learning and leading to better educational results.

Introduction

A critical factor in shaping educational systems is the need to develop human insights and capabilities effectively. The cultivation of human capital represents a central goal of education, emphasizing intelligence, skills, and character that enable this “brain capital” to navigate both local and global educational landscapes constructively (Okafor & Bello, 2023). Nevertheless, the pursuit of high academic performance often imposes significant stress on students, teachers, and the overall school management system (Adeyemi, 2021).

In Nigeria, there are imprints of several socio-economic indicators on students' academic performance, like gender, family income, parental support, study habits, teacher effectiveness, school environment, community content, and curriculum quality (Musa, 2020; Oladipo, 2019). The said factors collectively account for the high level of academic success that students will attain. Schools play an essential role to make all its programs, activities, infrastructures, and curricula in sync with the community needs (Abubakar, 2022). The students' achievements and adjustment are effects of the schools, but broader social environments like parents, peer groups, neighborhood, religious institutions, and youth organizations shape the same (Chukwu, 2021). Students also have a role to play themselves; it is through their individual differential abilities, temperaments, and motivations that they shape their behavior, aspiration, and learning achievement (Emeka & Aina, 2020).

In Nigeria, scholastic excellence and success are often attributable to the backing and participation extended to students by parents. Parents come in through communication about the activities in the school, expectation of the child becoming highly educated, a contemplate about the source of revenue from home conditions, and interactions with their schools by way of events, governance, and information-sharing (Adewale, 2019). It has been found that students who have parents that are involved and participate in this process with them have higher outcomes (Ibrahim, 2022). Parents' encouragement, vis-à-vis science, profusely raises the attitudes with which the students appear in the class as well as their performance (Ogunleye & Salami, 2018). Recognized as a flagship science discipline in the Nigerian senior secondary educational system, Biology may have crucial impacts on students' academic aspirations at large (Okeke & Nwosu, 2021). Understanding the concept of Biology will then help the students gain sound analytic acumen, the necessary skill at problem solving, and the competence to reason out complex phenomena. In mapping agreements in other disciplines, Biology is seen to be a very important part.

However, numerous Nigerian students are challenged when trying to understand Biology including the concepts under its arms such as genetics, mitosis and meiosis, plant and animal physiology, biodiversity, and ecosystems (Onyeka, 2022). Failure at these areas can contribute negatively in areas of student motivation, achievement, conceptual understanding (Fatoki, 2023). Biology is a broad field, and there was diversity in the understanding of values of this subject. Some of these values were seen as resulting from the consideration of these concepts and their connections to daily lives, thus considering biology awareness as a core-essentially crucial aim to teach. Biology, as taught in schools or elsewhere, profoundly influences how we think about ourselves, how we live in this vast mansion of nature, and how one man's decision or action can all collectively impact life all over the universe. In truth, biology consciousness is a belief in doing what's right on Earthlib," and it will talk about the knowledge of life and not the knowledge in life only.

Mapping gaps within any topic, especially regarding the least mastered competencies of Biology students, provides key areas of understanding for teachers to change their teaching methods, curriculum delivery, and assessment strategies (Adetunji & Yusuf, 2023). To face the challenges of global knowledge economies, in any case, the Nigerian education sector should equip students with learning competencies needed for higher academic success and securing opportunities for future professional success in the 21st century (Okafor, 2022). Molecular biology is at the heart of developments in genomics, biotechnology, medicine, and agriculture, which are so salient in the global contemporary life sciences. Things like DNA replication, transcription, translation, gene regulation, molecular interactions are key topics for graduate-level training in biology. Despite their importance, these concepts are abstract, dynamic, and multilayered, creating challenge in integrating molecular biology, at spatial and temporal levels. For instance, research consistently reveals that most students fail while mastering the higher conceptual complexities of molecular biology as they settle into mere memorization. This summary approach is prejudicial to the achievement of the success and near-genetic understandings required for their professional practices in the biological, cognitive, and sociological sectors in any kind of knowledge transfer when applied to research and its broad professional scope.

Post-industrial technologies such as virtual reality, simulations, and IT-based collaborative tools have significantly enhanced modern education by promoting experiential and inquiry-based learning. In molecular biology, simulations enable learners to visualize complex processes, such as lymphocyte–antigen interactions, thereby improving conceptual understanding. These tools create multisensory environments that support active exploration and immediate feedback, aligning with experiential learning principles (Muogbo et al., 2025). When cognitive load is minimized and scaffolds are provided, simulations effectively strengthen reasoning and knowledge construction (Obikezie et al., 2023). Similarly, problem-solving frameworks improve learners' analytical abilities in science (Okafor, 2019). Authentic assessment and appropriate instructional strategies further enhance learning outcomes (Nnorum & Okafor, 2011). However, effective implementation depends on teachers' technological competence (Nneka & Okafor, 2013). Additionally, integrating relevant physics content fosters skill acquisition and application (Okafor, 2018), while addressing learning difficulties improves comprehension (Okafor, 2015). These digital technologies collectively advance meaningful and effective education.

Adaptive digital simulations, which offer flexible adjustments to content, difficulty, and feedback in response to learners' performance, have more recently been introduced to accommodate individual differences in students' prior knowledge base and learning pace. Deeply grounded in constructivist learning theory and inating work of cognitive load (John Sweller, 1988), adaptive technologies aimed to personalizing learning pathways officially aim to ensure that students are challenged and supported at appropriate levels. In such complex domains as molecular biology, where misconceptions often linger with learners long past prerequisite teaching, adaptive system may serve in identifying the exact conceptual gaps and delivering remediation appropriately.

Despite all the validation and findings worldwide, the demonstration of digital simulations within science education tools as an advanced concept, holds thin at postgraduate level in a developing context such as that in Nigeria. In Delta State, these are becoming an obstruction to the postgrad programs offered in biological sciences, such as scarce resources of the laboratory, overcrowded classes, and very dissentient student preparedness. These obstacles do not bear well with the teaching of molecular biology in an interesting manner, as it includes enormous sophisticated laboratory practicals which need a lot of demonstration capacity and visualization tools. Embedding adaptative digital simulations may have the potential to offer a cost-effective counterbalance to traditional instruction by fostering clearer scientific concepts and self-directed study in the process.

Wade (2013) reports that the introduction of technology improves student learning as a causal effect. Inherent in this claim, however, is the proposition that adaptive digital simulations are an effective medium for creating better effective teaching and learning vis-a-vis subject/outcome well-being, utility, and adaptability. Consequently, this intensifying study should seek to examine what influence these tools have on graduate students' object concepts in molecular biology, within the Delta State socio-educational context. Outcomes from its study may include assessing the use of technology that develops conceptual themes in molecular biology, Delta State, Nigeria, among graduate students, as opposed to a comparison of adaptive-technology affected learning outcomes with those of traditional teaching systems. Whatever information the study acquires will help in any curriculum reform, instructional design, and technology integration, especially into STEM education at the graduate level-buildings that are consistent with best practices currently canon concerning educational technology.

Statement of the Problem

Molecular biology nested along graduate biological sciences, biotechnology, medicine, and related research. At the graduate level, an advanced understanding is demanded in complex processes such as gene expression, molecular regulation, signal transduction pathways, and genomic interactions. In spite of taking advanced coursework students struggle to integrate abstract molecular facts into coherent and functional frameworks. A lot of learning remains procedural or memorization-based rather than conceptual and analytical, thereby significantly minimizing the students' capacity to use their knowledge in an effective manner in a research and problem-solving context.

Embarrassed at how it emphasizes molecular biology, explanatory problems remain in imaging. As it is invisible, and yet alive, it also is in motion and registering a developed cycle. This arising from it would be hard to hunker comfortably with. These discordant conditions would perhaps affect student ability to mentally create visual matter in the mind. Along with any given information provided, students thus must learn ponderous levels of significance. This invitation to critical thought is, therefore, very thought-provoking. With the advent of technology and globalization, knowledge repositories are endless, but the ghost that accompanies such repositories demands a separating of the "wheat from the chaff." Textbook is unable to be calculably able to separate the learning, what is a learning process apart from it, a part. Also, what amounts to laboratory practices is when people use nothing that has not been at least visually conveyed through books, and if one day they truly shall meet a specimen, then it would hardly serve any useful purpose. This is an invitation helplessly for nothing

In a nutshell, difficulties in teaching molecular biology result from contextual factors outside the teaching-learning enterprise. Such factors would include the varied levels of technological infrastructures making use of which emerging graduate programs in biology function within other places and points to class-size configurations quite unwieldy in relation to the arrays of students' knowledge and cognition. Despite these probable limitations of understanding the concept on molecular biology, there is increased technology advocacy in all spheres of education worldwide. Nevertheless, the pedagogical value of these digital technologies very much depends on while integrating them into the very fabric of instruction-there is no less need for thought out procedure, accessibility, and effective relation to the curriculum itself. Interactive computer simulations that adapt based on learner response from moment to moment, as well as according course content and feedback to meet individual performance levels, offer a promising instructional alternative. By allowing students to manipulate various conditions of chemical reactions and work with instant feedback to visualize the course of events, students can improve their conceptual learnings and misconceptions. However, some evidence-based research regarding the effective use of adaptive digital simulations at the graduate level, especially in the Nigerian university system, is still required. Most studies remain at the secondary or undergraduate levels and predominantly originate from developed countries, exposing a research gap in the right context.

Additionally, the adaptation of the digital tools in the higher education sector of Nigeria should not have been presumed to relate directly to the improvement of the learning outcomes. Certainly, there is scanty evidence to help one assert that adaptive simulations contribute much to the enhancement of students' understanding of molecular biology relative to the happening at master level, using the more traditional forms of educational instruction. Therefore, in the absence of such evidence, members of the academic community might remain in a state of ignorance when pertinently considering incorporating and investing in adaptive educational technologies. Therefore, the research problem that the authors of this study wish to address is that there seems to be a minimal empirical understanding of how adaptive digital simulation affects graduate students' understanding of molecular biology in Delta State, Nigeria. Precisely, it is not well understood as to whether or not the use of adaptive digital simulations would greatly lead to the improvement of conceptual mastery compared to conventional teaching approaches. This study is pertinent in that it is meant to inform instructional leaders designing more productive science and mathematics programs at the graduate level to enhance their applicable research capacity in addition to the experimental models in Biological Science within the region.

Literature Review

Conceptual understanding in terms of being able to connect knowledge, apply principles elsewhere, and explain underlying causes instead of rote facts are involved in considering molecular biology-a science that requires one to know the dynamic relationship between the basic entities of DNA, RNA, proteins, and control systems at various levels of organization. It is thought that, in addition to remembering pathways like replication and transcription; graduate students should also do so by scrutinizing the regulation network and interpreting their results. However, studies have shown that in the realm, learners still maintain fragmented knowledge structures, and, more, misconceptions of molecular and cellular biology persist (Stevie & Sun (2006); Prince & Felder). The abstract concepts and microscopic perspective of molecular-level events are greatly demanding cognitively. With mental images of the invisible processes, students must then relate such images to symbolic representations including diagrams and chemical equations that specify their functional outcomes in biology. Without providing additional context, as per the theory of cognitive load (Sweller, 1988), the demand of learning can be more detrimental to the mental system of the learner than it is helpful. Consequently, changes will need to be made in the teaching of molecular biology to pave way towards what can be seen as deeper conceptual learning at the MSc level.

Digital models are on the rise in science-related instruction because they are dynamic, making it possible to simulate complex systems. Simulation permits learners to adjust variables, form hypotheses, and observe real-time outcomes-all the while remaining dynamically linked to that environment. Here, computer simulations represent constructivist learning-themed experiences at the level of a theoretical branch or application, where beneath the principles establishing theory with "realism," learners are engrossed in constructing knowledge and then retain practical ways of sustainable self-generation. Witness Ton de Jong (2010) contending that computer simulations support an inquiry approach in learning seriously. So did Nienke Rutten, van Joolingen, and van der Veen (2012) conclude that simulations significantly enhance conceptual understanding of science when learning is supported by teaching. Useful tools in areas of application where laboratory experiments are scarce or difficult due to cost, safety, or equipment must therefore be molecular biology.

Empirical finding have shown that simulations enhance visual solidarity and that change occurs in the conceptual arena. They keep students fascinated. But somehow their efficiency lies in the kind of scaffolding, prior knowledge, and instructional design in use. Hence, simulations are not self-sufficient; one needs to teach with them. Adaptive digital simulations are a more sophisticated form of educational technology. These systems adapt the learning pathway to the student's responses to assure that the student receives differentiated feedback and content based on their progress. The idea put by this approach what cognitive load theory and self-regulation about metacognition, which puts the learner in the level of an appropriate challengingly learnt. Personalization has been shown to enhance motivation, reduce frustration, and improve learning outcomes in complex subject areas. In this light, adaptive systems can facilitate deeper understanding by identifying misconceptions and targeting relevant gaps in valuable ways. In molecular biology at graduate level, where students may be from a variety of backgrounds in academic ability, the existence of adaptive simulations might also act as a bridge to fill some of the gaps between students of differing background knowledge and research experience.

Adaptive design leads to metacognitive awareness by offering immediate feedback and analytics of students' performances. Such attitude encourages reflective learning so important for a higher level of scientific instruction. There is virtually no educational research on adaptive simulations in higher education and research, and scant ongoing adaptive research in general has been towards the sub-Saharan African region. Universities in Nigeria have been allotting most of their resources towards infusion of digital learning tools over the last few years amid a greater global orientation towards blended and distance learning. However, these constructs of digital literacy are highly dynamic structures and are often shackled by ill-designed universities with an inadequate support system. Herein lies the principle impediment to the implementation of these digital forms in the instruction of national curricula.

Within the resource-deprived setting within which they exist, the universities in Delta State that offer graduate programs in biological sciences are further deprived in the realm of laboratory-based practical instruction. The ultimate application of novel learning tools, in this case, digital simulation, is to streamline and upraise the understanding of concepts; however, this comes with the caveat: weaving success out of these tools is dependent on a smooth operation of more contextual aspects, including the right access to the web, technical help to willing students, and curriculum contents hurriedly designed to pave way for students themselves. Given there is no study to examine the effect of digital adaptive simulation for Nigerian postgraduate science education, gaps in knowledge are wide and glaring.

Theoretical Framework

This study is grounded in constructivist learning theory, cognitive load theory, and adaptive learning principles, where this approach focuses on building student learning experiences in a dynamic way and shifting the emphasis from instruction to encourage students to learn, while cognitive load theory allows instructional designers to optimize working memory load (John Sweller, 1988). Adaptive learning systems manifest these theories by customizing instructional content as per students' needs. In this particular study, we intend to look at ways of making conceptual understanding in molecular biology viable to graduate students in Delta State through adaptive digital simulations, considering the strong theoretical precedence but weak empirical investigatory support in the particular study context. Hence, this study seeks to take a significant step in shedding light on effective technology-aided learning at the graduate level of STEM education.

Research Hypotheses

The following null hypotheses will guide the study and will be tested at 0.05 level of significance:

H_{01}: There is no significant difference in the pre-test conceptual understanding scores of graduate students in molecular biology between the experimental group (adaptive digital simulations) and the control group (traditional instruction).

H_{02}: There is no significant difference in the post-test conceptual understanding scores of graduate students exposed to adaptive digital simulations and those taught using traditional instructional methods.

H_{03}: Adaptive digital simulations have no significant effect on graduate students' conceptual understanding of molecular biology after controlling for prior knowledge.

H_{04}: Prior knowledge does not significantly predict graduate students' conceptual understanding of molecular biology when exposed to adaptive digital simulations.

H_{05}: There is no significant relationship between students' engagement with adaptive digital simulations and their post-test conceptual understanding scores.

Methodology

Research Design: The study was designed with quasi-experimental- pretest, post-test controls. The choice of a quasi-experimental pre-test, post-test control group design was because the study had to be conducted in intact classes. Since it was not feasible to do single-student random assignment, the between-student discrepancy/problem is a drawback to be considered. This has enabled us to compare learning outcomes under conditions of adaptive digital simulations (experimental group) and conventional instructional techniques (control group) with the pre-test as a control for substances.

Area of the Study: The study was conducted in Delta State, Nigeria. The Nigerian state of Delta has several public universities offering graduate programs in Biological Sciences and related disciplines. These include: Delta State University, Abraka (DELSU), University of Delta, Agbor (UNIDEL) and Delta State University of Science and Technology, Ozoro (DSUST). These institutions offer postgraduate programs in disciplines like Molecular Biology, Biochemistry, Biotechnology, and other biological sciences.

Population and Sample: This study included graduate students in the field of Molecular Biology and related postgraduate course programmes at selected public universities in Delta State during the 2025/2026 academic session. To select participants in such a way that is practical and representative, a multi-stage approach was taken. In the first stage, some public universities in Delta State that offered postgraduate programmes in Biological Sciences were selected purposively in order to provide a population that was the most appropriate for the study. In the second stage, it was decided that departments offering Molecular Biology or courses in a related field should be identified. Finally, intact graduate courses from these departments were selected, with one assigned as the experimental group and another serving as the control group in a comparative way.

There was a very conscious decision to retain the classes intact in order to ensure smooth implementation of interventions, without disturbing the academic schedule unduly, yet providing a complete natural environment, also ensuring that the same teaching context was given throughout, so that any deviation in performance could have nothing to do with the variability in teaching contexts. A total of 76 graduate school students eventually took part in the study. The sampling was an acceptable balance and representation of Molecular Biology and related programmes' students and was strongly conducive to assessing the impact of the experimental intervention.

Instrumentation: Data were collected using a combination of researcher-developed and digital instruments, each carefully selected to address specific aspects of the study:

1. Molecular Biology Conceptual Understanding Test (MBCUT):

A researcher-developed instrument designed to assess students' understanding of core molecular biology concepts, including DNA replication, transcription, translation, gene regulation, and molecular interactions. The test comprised multiple-choice and short-answer conceptual questions, providing both breadth and depth in evaluating conceptual mastery.

2. Adaptive Digital Simulation Package (ADSP):

An interactive digital platform that dynamically adjusted instructional content and feedback based on students' responses and performance levels. The simulation allowed participants to manipulate molecular processes and provided immediate corrective feedback, promoting active learning and deeper conceptual understanding.

3. Students' Perception Questionnaire (SPQ):

A structured Likert-scale questionnaire designed to capture students' perceptions of the simulation's usability, engagement, and effectiveness. This instrument provided insights into learners' experiences and attitudes toward digital simulation-based instruction.

4. Engagement Log Data:

Automatically generated usage data from the simulation platform were collected to measure the frequency and duration of interaction. These logs provided an objective measure of students' engagement with the simulation, complementing self-reported perceptions. Together, these instruments enabled a comprehensive assessment of students' conceptual understanding, engagement, and attitudes toward the intervention, allowing for triangulation of data to strengthen the validity of the findings.

Validity of the Instruments: The instruments were subjected to face and content validation by experts in Molecular Biology, Educational Technology, and Measurement and Evaluation. A table of specifications guided the development of the conceptual understanding test to ensure adequate coverage of content areas and cognitive levels.

Reliability of the Instruments: The Molecular Biology Conceptual Understanding Test was pilot-tested using graduate students outside the study sample. Reliability was determined using Cronbach's Alpha, and a coefficient of 0.70 or above was considered acceptable. The internal consistency of the Students' Perception Questionnaire was also established using Cronbach's Alpha method.

Procedure for Data Collection: Data collection for the study was carried out in four main stages to ensure a systematic and coherent process.

Pre-test: Before the instructional intervention began, both the experimental and control groups were given the Molecular Biology Conceptual Understanding Test (MBCUT). This initial assessment helped establish a baseline of students' knowledge and understanding of key molecular biology concepts.

Instructional Intervention (6–8 weeks): The experimental group received instruction enhanced with adaptive digital simulations, allowing students to interact with molecular processes and receive immediate feedback. The control group was taught using conventional methods, including lectures, textbooks, and classroom discussions, reflecting standard instructional practice.

Post-test: At the end of the intervention period, both groups completed the same conceptual understanding test. This allowed for a direct comparison of knowledge gains between students who experienced the digital simulations and those taught via traditional methods.

Perception Survey: After the intervention, the Students' Perception Questionnaire (SPQ) was administered to the experimental group to gather feedback on the usability, engagement, and overall effectiveness of the adaptive digital simulations.

This stepwise approach not only measured changes in conceptual understanding but also captured students' experiences and engagement with the innovative instructional method, providing a comprehensive view of the impact of the intervention.

Data Analysis: The study meticulously organized and analyzed data to evaluate the impact of an instructional intervention involving adaptive digital simulations on students' conceptual understanding and engagement. Using the Molecular Biology Conceptual Understanding Test (MBCUT), pre- and post-test scores were compared within and between groups through paired and independent t-tests to assess knowledge gains. Descriptive statistics summarized students' performance and perceptions gathered from the Students' Perception Questionnaire (SPQ), which highlighted attitudes toward usability and engagement. Additionally, engagement data from the Adaptive Digital Simulation Package (ADSP) provided objective measures of interaction, such as access frequency and session duration, to correlate active participation with learning outcomes. The study's triangulated approach—combining test results, perception surveys, and engagement logs—strengthened the reliability of the findings, all while testing hypotheses at a 0.05 significance level to determine the effectiveness of the intervention comprehensively.

Ethical Considerations: Permission was obtained from the relevant university authorities. Participants provided informed consent before participating in the study. Confidentiality and anonymity were maintained throughout the research process, and participation was voluntary.

Results

H_{01}: There is no significant difference in the pre-test conceptual understanding scores of graduate students in molecular biology between the experimental group (adaptive digital simulations) and the control group (traditional instruction).

Table 1: Independent Samples t-test Showing Difference in Pre-Test Scores Between Experimental and Control Groups

Group	N	Mean ($\bar{X}$)	Standard Deviation (SD)	t-value	df	p-value
Experimental Group	38	42.63	6.84	0.57	74	0.571
Control Group	38	41.78	7.12			

To test this hypothesis, an Independent Samples t-test was conducted to compare the pre-test scores of students in the experimental and control groups before the instructional intervention. According to the calculated p-value (0.571) from the hypothesis test, the null hypothesis (H_{00}) could not be rejected at the significance level of 0.05 ($p > 0.05$); meaning, there is no scientifically or statistically significant difference in terms of the pre-test conceptual understanding score between the experimental and control groups prior to the training intervention. It could be inferred from this finding that both groups possessed a similar level of molecular concepts knowledge during their initial exposure to adaptive digital simulations. Since there was not a significant difference, it was confirmed that differences observed in post-test scores could in fact be attributed to a treatment effect (adaptive digital simulation) rather than any difference that might have existed in their pretest conceptual understanding. The current result supported the internal validity of the research since it confirmed that both groups started out from an approximately equivalent academic status in molecular biology.

H_{02}: There is no significant difference in the post-test conceptual understanding scores of graduate students exposed to adaptive digital simulations and those taught using traditional instructional methods.

Table 2: Independent Samples t-test Showing Difference in Post-Test Scores Between Experimental and Control Groups

Group	N	Mean ($\bar{X}$)	Standard Deviation (SD)	t-value	df	p-value
Experimental Group	38	71.84	8.25	4.62	74	0.000
Control Group	38	63.17	9.03			

Since the p-value computed (0.000) is lower than the 0.05 level of significance ($p < 0.05$), the null hypothesis (H_{02}) was rejected, which indicates that there was a significant difference in post-test conceptual understanding scores between the experimental and control groups. Graduate students exposed to adaptive digital simulations performed significantly better than those taught using traditional instructional methods.

$H_0$3: Adaptive digital simulations have no significant effect on graduate students' conceptual understanding of molecular biology after controlling for prior knowledge.

To test this hypothesis, an Analysis of Covariance (ANCOVA) was conducted with post-test scores as the dependent variable, pre-test scores as the covariate, and instructional method (experimental vs. control) as the independent variable.

Table 3: ANCOVA Showing Effect of Adaptive Digital Simulations on Conceptual Understanding Controlling for Pre-Test Scores

Source	Type III Sum of Squares	df	Mean Square	F-value	p-value	Partial η^2
Instructional Method	1387.24	1	1387.24	28.56	0.000	0.28
Pre-test (Covariate)	842.17	1	842.17	17.34	0.0638	0.19
Error	3592.63	73	49.22			
Total	5821.04	75				

The p-value for operational instruction (0.0638) was less than 0.05, rejecting the Null Hypothesis ($H_0 3$); with control for the prior knowledge of students, adaptive simulation resorted to high effects on both the conceptual understanding of molecular biology. It is hence concluded that the substantial change in the experimental group could be a consequence of the actuated system itself instead of the existing levels of ability. A partial η-squared value (η^2=. 28) implies a large effect size, meaning that the adaptive simulation accounted for 28% of variance in the post-test scores even after the elimination of the pre-test scores.

Hypothesis Four ($H_0 4$)

$H_0 4$: Prior knowledge does not significantly predict graduate students' conceptual understanding of molecular biology when exposed to adaptive digital simulations.

A simple linear regression was conducted with pre-test scores as the predictor variable and post-test scores of the experimental group as the dependent variable.

Table 4: Regression Analysis of Pre-Test Scores Predicting Post-Test Scores

Predictor	B	SE B	β	t-value	p-value	R^2
Pre-test Score	0.47	0.12	0.42	3.92	0.000	0.18

Since $p < 0.05$, the null hypothesis ($H_0 4$) was rejected.

The pre-test score was significantly related with post-test performances of students in experimental groups. Thus, the results indicated strongly that the prior knowledge of the students was only moderately instrumental for their post-test outcomes, but it was the adaptive simulation that ensured tremendous gains on the concepts. With an R-square of 0.18, prior knowledge does explain a variance of 18% in post-test scores. In other words, one's initial ability is a considerable factor, while the intervention played a central role in enhanced teaching and learning.

Hypothesis Six ($H_0 5$)

$H_0 5$: There is no significant relationship between students' engagement with adaptive digital simulations and their post-test conceptual understanding scores.

A Pearson correlation analysis was conducted between students' engagement (log data: time spent, interaction frequency) and post-test scores.

Table 5: Correlation Between Engagement and Post-Test Scores

Variable 1	Variable 2	r	p-value
Engagement	Post-test Score	0.62	0.000

Since $p < 0.05$, the null hypothesis ($H_0 5$) was rejected.

The relationship between the students' engagement with the adaptive simulations was positively noted in terms of the students' conceptual understanding of molecular biology. This finding implies that the extent of their interaction within the simulation platform was conducive to better learning outcomes, confirming the efficacy of hardwiring an active participation in technology-mediated instruction.

Discussion

The data from the present study provides compelling evidence that adaptive digital simulations have been found to be significantly beneficial for improving the content conceptual understanding of molecular biology among postgraduate students in the Delta State, Nigeria. Each hypothesis considers different aspects of learning outcomes, engagement, and influence of prior knowledge, and these results can be interpreted in the context of the existing literature.

Hypothesis one (H_{01}) was tested to see if there were differences pretest between the experimental and control groups. The results showed that there were no statistically significant differences, thus establishing the two groups had an equal base of perceiving molecular biology concepts. This was crucial in relation to ensuring the internal validity of this quasi-experimental design and making sure that the subsequent differences gained in the posttest could be attributed to the instructional intervention rather than preexisting differences (Creswell & Creswell, 2018).

The second hypotheses indicates that there were notable performance improvements in the post-test scores and gains from the experimental group relative to the control group. This supports the application of adaptive digital simulations to enhance students' understanding of molecular biology's concepts. This corroborates earlier studies demonstrating that computer-based simulations could significantly enhance visualization, conceptual reasoning, and cognitive engagement in real-world learning in science (Rutten, van Joolingen, & van der Veen, 2012; de Jong, 2010). In molecular biology, activities like DNA replication, transcription, and translation happen at the microscopic level where the events are abstract and too dynamic to be directly observed. Hence, in conventional lecture-based teaching technique, the static diagrams and verbal explanations sometimes fail to reinforce effective creation of mental models (Prince and Felder, 2006). Consequently, adaptive theory would consider that adaptive simulations that give flexibility regarding personal interaction and targeted feedback allow for a holistic structure, giving learners the power to interact with control systems at the molecular level, receive immediate corrective feedback using some kind of embedded documentation, and solve misconceptions (Jonassen, 1999).

The third hypothesis included an ANCOVA analysis to control for pre-test scores and demonstrated (along with direct testing of the Intraclass Correlation) a strong positive effect on learning outcomes. Could this intervention result in 'negative transfer', as applied in general? That is, could prior learning now be viewed as a barrier or negative influence on the development of learning under this new treatment? Possible negative cross contextual effects would be minimized or potentially erased out through an active learning environment. Hypothesis four (H_{03}) used ANCOVA to control for pre-test scores, confirming that adaptive digital simulations had a significant effect on conceptual understanding even after accounting for initial ability. This finding aligns with cognitive load theory (Sweller, 1988), which posits that instructional interventions that scaffold learning and manage cognitive load can enhance comprehension regardless of prior knowledge. By providing individualized guidance, adaptive simulations reduce extraneous cognitive load and facilitate schema construction, enabling students to process complex molecular information more efficiently.

Regression analysis for hypothesis four (H_{04}) revealed that prior knowledge significantly predicted post-test performance but only accounted for 18% of the variance. This means that students' background knowledge contributes to learning outcomes; however, the adaptive simulation itself is the primary contributor to conceptual gains. These results align with the literature on science education with respect to adaptive learning technology, emphasizing that differentiated instructions based on individual learners are possible (de Jong, 2010; Rutten et al., 2012).

Hypothesis 5 (H_{05}) reigns in a very strong positive correlation between student engagement with the simulation and post-tests. This underscores that it is very necessary to allow learners to interact with digital environments directly. Other such studies found that learner engagement is highly linked to the effective use of simulation for learning; the more students are allowed to explore, manipulate, and check variable occurrences in a simulation, the higher their constraint validation (de Jong & Van Joolingen, 1998; Rutten et al., 2012). This means that instructors must increasingly dissociate with any level of interaction in open-ended problems for engagement. The molecular biology workshop yielded statistically significant improvements in the post-test scores of participants compared to the pre-test ones. Workshop duration being similar for all, observations suggested that the five-day workshop time frame was sufficient to incubate and effect learning. Everyday, the participants tended to develop their interest and confidence through hands-on practical laboratory sessions, which gave way to lectures done in the classroom.

Implications for Teaching Molecular Biology in Nigerian Graduate Programs

The present study has considerable implications for the teaching of molecular biology within graduate programs in Nigeria. One impetus towards this is to enhance the incorporation of adaptive digital simulations into the curriculum. These simulations enhance comprehension of centrifugation theory and conversations on the abstract and dynamic subject matter of molecular biology. Indeed, computational simulations, on one side, move forward in student ability to envisage and manipulate molecular processes without alternately offering a never before seen attitude to visualizations of molecular processes. Either way, the same simulations fill in gaps in students' expectations, as opposed to absorbing expensive laboratory facilities, where opportunities speech may be viewed as ignorable. Finally, adaptive simulations were based on the research questions and suggested further performance assessment within the context of arts education. Instructors had to consider the level of arts education into the curriculum of education to design a final assessment from the findings of this study.

In this context, the study's positive results indicate the implications of adaptive simulations in curriculum design and policy-making. Utilization of such technology for graduate-level molecular biology courses will increase learning outcomes and especially in resource-constrained environments. Nigerian universities may also introduce blended learning models centered around traditional lectures alongside various technology-mediated simulations, making it a more thorough and more beneficial teaching model. In conclusion, success in the assimilation of adaptive simulations entails faculty development. Instructors need to work on training in pedagogical design, implementation, and evaluation of simulation-based learning to help guarantee that the technology actually fits with educational objectives, complements courses, and yields results in learning outcomes. The research generally concludes that the careful integration of adaptive digital simulations in the context of teaching molecular biology enhances conceptual understanding, encourages student participation, and advances the overall excellence in postgraduate science education in Nigeria.

Conclusion

In sum, hypothetical evidence stares very factually at one of adaptive digital simulation's cachet for being a fancy instructional tool, one that shapes, strengthens the student's innate and induced-over recent, prior time-teacher, guess at meanings in such a powerful learning setting in molecular biology mainly for graduate students. Unlike placebo-control trials where improvements are established by t-tests and ANCOVA at the most, the improvements are not only statistically significant but also practically very significant. In this study, engagement with the simulations and prior learning interactively influenced the outcomes in a way that portrays the interplay between learner characteristics and instructional design. These results corroborate past literature that has favorably spoken of the usefulness of computer-based/adaptive learning technologies in science (de Jong, 2010; Rutten et al., 2012; Prince & Felder, 2006) and extend the evidence base to graduate-level STEM education in the Nigerian context. Implementation of adaptive digital simulations in molecular biology programs could bring about a high degree of improvement in learning outcomes, deeper understanding of concepts, and much support for the inculcation of graduates that are research-ready.

Recommendations

Based on the findings of this study, several recommendations are proposed to enhance the teaching and learning of molecular biology in Nigerian postgraduate programs. First, universities should integrate adaptive digital simulations in molecular biology teaching. Such tools have a proven track record of enhancing understanding in terms of concepts. This is through an interactive, visual, and personalized experience and should be harnessed in teaching. Universities should focus on procuring or developing high-quality adaptive simulations as resources for allowing students to explore the complexities of molecular processes beyond the weaknesses of traditional modes.

Educators could employ active learning methods for enhancing student engagement. This survey showed an intense correlation between interactive engagement with instructional materials and high-quality learning. To foster student engagement, educators should develop activities for students to manipulate variables, test hypotheses, and reflect on outcomes, and use these interactions to impart knowledge.

One more thing: the true value of adaptive simulations must be optimized. The scope of graduate education is very wide, as the students have diverse academic backgrounds; therefore, adapted nature of systems is the key to diversifying their feedback. Depending on their performance, engaged scaffolded activity streams, and remediation will be subsidized to suit continuous improvement in the learning outcomes.

Instructors and school administrators should also explore blended educational approaches which mix standard instruction along with the computer-aided simulation and other digital resources. Enhanced use of technology in learning can also provide a means of overcoming resource challenges (like an inadequate number of science laboratories) while ensuring high academic standards. The passed method may also serve for building up research-ready graduates who are a breed of good theoretical knowledge along with practical skills.

Teacher education programs must be formed to train faculty on a one-on-one usage of adaptive simulations. The training may be intended for covering matters on pedagogical principles, instructional design, technology integration, and strategy of assessment, so that faculty are competent to use simulations in a manner that is connected with learning objectives and catered to student engagement to improve learning outcomes.

The application of these recommendations will significantly enhance the quality of graduate molecular biology education in Nigeria, foster the development of deeper conceptual understanding, and prepare students for further studies and involvement in professional practice in biological sciences.

References

Abubakar, A. (2022). *School programs and community relevance in student performance*. Ibadan, Nigeria: Education Press.

Adetunji, R., & Yusuf, M. (2023). *Mapping least mastered competencies in biology: Implications for curriculum delivery*. Journal of Science Education in Nigeria, 12(1), 45–60.

Adewale, S. (2019). *Parental involvement and student achievement in Nigerian secondary schools*. Abuja, Nigeria: National Education Research Council.

Adeyemi, T. O. (2021). *Stress and academic performance in Nigerian schools: Implications for students and teachers*. Lagos, Nigeria: Academic Publishers.

Chukwu, E. (2021). *Social environment influences on student adjustment and achievement in Nigeria*. Nigerian Journal of Educational Studies, 18(2), 77–92.

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). Thousand Oaks, CA: SAGE Publications.

De Jong, T. (2010). *Computer simulations in science education: Supporting inquiry learning*. Science Education Review, 6(1), 15–24.

De Jong, T., & van Joolingen, W. R. (1998). *Scientific discovery learning with computer simulations of conceptual domains*. Review of Educational Research, 68(2), 179–201. https://doi.org/10.3102/00346543068002179

Emeka, J., & Aina, T. (2020). *Individual differences and academic achievement among Nigerian students*. Journal of Educational Psychology in Africa, 7(1), 34–49.

Fatoki, K. (2023). *Challenges in learning molecular biology in Nigerian secondary schools*. African Journal of Biology Education, 9(3), 101–115.

Ibrahim, M. (2022). *The role of parental support in students' academic outcomes in Nigeria*. Lagos: University of Lagos Press.

Jonassen, D. H. (1999). *Computers as mindtools for schools: Engaging critical thinking* (2nd ed.). Upper Saddle River, NJ: Prentice Hall.

Muogbo, U. F., Okafor, T. U., & Okafor, C. F. (2025). Experiential Learning Strategy as a Predicator of Male and Female Students Interest in Computer Studies in Nnewi Education Zone, Anambra State, Nigeria. *IRASS Journal of Arts, Humanities and Social Sciences*, *2*(5), 112-116.

Musa, A. (2020). *Socioeconomic factors and academic performance of Nigerian students*. Kaduna: Nigerian Educational Research Council.

Nneka, R. N., & Okafor, T. U. (2013). Assessment of Science Teachers' Level of Computer Literacy and Usage in Colleges of Education: Implication for Global Competitiveness. *African Journal of Education, Science and Technology (AJEST)*, *1*(1), 250-258.

Nnorom, N., & Ukafor, T. (2011). Authentic assessment method in science: Study of issues for teachers. *ANSU Journal of Integrated Knowledge*, *1*(1), 202-209.

Obikezie, M. C., Ezeliorah, B. A., & Okafor, T. U. (2023). Effect of generative learning model on secondary school students'academic achievement in Chemistry. *UNIZIK Journal of Educational Research and Policy Studies*, *15*(3), 45-55.

Ogunleye, D., & Salami, B. (2018). *Parental influence on science learning outcomes in Nigerian schools*. Science Education Review, 15(2), 59–74.

Okafor, P. (2022). *Learning competencies and 21st century education in Nigeria*. Enugu: Academic Press.

Okafor, P., & Bello, H. (2023). *Human capital development and educational outcomes in Nigeria*. Journal of African Educational Research, 14(1), 11–29.

Okafor, T. U. (2015). Difficulties Encountered by Secondary School Physics Students in Answering Mathematical Related Physics Questions. *American Academic & Scholarly Research Journal*, *7*(6).

Okafor, T. U. (2018). Identification of physics contents that can promote entrepreneurial skills among senior secondary physics students. *Nnadiabule Journal Education in Africa*, *3*(2), 39-51.

Okafor, T. U. (2019). Effect of Polya's Problem Solving Technique on the Academic Achievement of Senior Secondary School Student in Physics. *European Journal of Physics Education*, *10*(1), 38-48.

Okeke, C., & Nwosu, E. (2021). *Biology education and students' analytical skills development in Nigeria*. Nigerian Journal of Science Education, 20(1), 23–40.

Oladipo, F. (2019). *Determinants of student academic success in Nigerian secondary schools*. Ibadan: Educational Insights.

Onyeka, L. (2022). *Difficulties in mastering key biological concepts among Nigerian students*. African Journal of Educational Research, 11(4), 88–102.

Piaget, J. (1972). *The psychology of the child*. Basic Books.

Prince, M. J., & Felder, R. M. (2006). *Inductive teaching and learning methods: Definitions, comparisons, and research bases*. Journal of Engineering Education, 95(2), 123–138.

Rutten, N., van Joolingen, W. R., & van der Veen, J. T. (2012). The learning effects of computer simulations in science education. *Computers & Education*, *58*(1), 136–153. https://doi.org/10.1016/j.compedu.2011.08.001

Stevie, R., & Sun, P. (2006). *Misconceptions in molecular and cellular biology: Implications for graduate learning*. Journal of Biological Education, 40(2), 72–78.
Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science, 12*(2), 257–285. https://doi.org/10.1207/s15516709cog1202_4
Sweller, J. (1988). *Cognitive load during problem solving: Effects on learning*. Cognitive Science, 12, 257–285.
Ton de Jong, T. (2010). *Computer simulations in science education: Supporting inquiry learning*. Science Education Review, 6(1), 15–24.
Wade, R. (2013). *Technology integration and student learning outcomes: Evidence from science education*. Journal of Educational Technology, 10(2), 41–57.