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Pedagogical Effect of Computer Animated Simulation and Students Academic Performance in Biology Among Secondary School Students in Cross River State, Nigeria

[1]Ashiwere, Isaac Obogo; [1]Obi, Mathias Bebia; [1]Imong, Ann Obela; [2]Agiande, Innocent Undie; [1]Effiong, Effiom Etim; [1]Agbor, Catherine Kuko; [1]Aricha, Simon Ajah

[1]Department of Biology Education, University of Calabar, Nigeria
[2]Department of Physical Sciences Education, University of Calabar, Nigeria
[1]ashiwereisaac@gmail.com, ORCID ID.: https://orcid.org/0000-0002-3425-2471
[1]obimathias2013@gmail.com, ORCID ID.: https://orcid.org/0009-0004-1976-5801
[1]obelaanny@gmail.com, ORCID ID.: https://orcid.org/0009-0007-6896-5270
[1]agiandeinnocent@gmail.com, ORCID ID.: https://orcid.org/0009-0001-1707-7261
[1]effiome70@gmail.com, ORCHID ID: https://orcid.org/0009-0007-8744-9191
[1]catherinekukoagbor@gmail.com, ORCHID ID: https://orcid.org/0009-0005-3835-807X
[1]arichasimon@unical.edu.ng ORCHID ID: https://orcid.org/0009-0001-7908-5910

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Abstract

The study examined the pedagogical effect of computer-animated simulation on students' academic performance in Biology among secondary school students in Cross River State, Nigeria. It aimed to achieve two objectives, address two research questions, and test two null hypotheses. A pre-test, post-test, non-equivalent control group design was employed. The study population comprised all Senior Secondary II Biology students, with a sample of 221 students selected from four intact SSII classes in the Ogoja co-educational zone. Data were collected using the Biology Performance Test (BPT), whose validity and reliability were established. Descriptive statistics, including mean and standard deviation, were used to analyze the research questions, while ANCOVA was applied to test the null hypotheses. Findings revealed a significant difference in the mean performance scores of students taught using computer-animated simulation compared to the traditional lecture method. Specifically, a significant difference was observed between the experimental and control groups, $F(1, 220) = 14.895$, $p < 0.05$. However, no significant difference was found in mean scores between male and female students across both instructional methods, $F(1, 220) = 1.780$, $p > 0.05$. The study concluded that computer-animated simulation is more effective than the lecture method in enhancing students' academic performance. It is recommended that teachers should integrate this instructional strategy to improve students' learning outcomes.

1.0 Introduction

Technology has transformed education by introducing innovative tools that enhance learning experiences. One such tool, computer-animated simulation, has been recognized as an effective instructional strategy. This approach utilizes computer-generated models to replicate real-world processes, enabling learners to interact with and explore complex concepts in a controlled virtual environment. Unlike traditional teaching methods, which often promote passive learning, computer simulations encourage active participation, making learning more engaging and effective. Notably, incorporating computer simulations in science education enhances students' academic performance by facilitating the application of scientific knowledge to real-life situations (Murugesan, 2019), as cited in [1]. Similarly, the authors emphasized that computer simulations help learners transform abstract concepts into concrete knowledge, allowing them to connect theoretical content with real-world applications [1].

Biology explores living organisms and life processes, many of which are abstract and challenging for students to grasp through traditional teaching methods. Concepts such as cell division, photosynthesis, and genetic inheritance often become difficult to understand when presented through static textbook images or lectures [1], [2]. Computer-animated simulations address this challenge by offering interactive representations that allow students to visualize and manipulate these biological processes, reinforcing their understanding in ways that conventional methods cannot. For example, a mitosis simulation enables students to observe and control each stage of cell division, providing a dynamic learning experience. Similarly, a photosynthesis simulation allows learners to adjust environmental variables such as light intensity and carbon dioxide levels, helping them grasp cause-and-effect relationships more effectively [3]. By engaging with these interactive models, students not only enhance their comprehension of biological concepts but also improve academic performance and knowledge retention. This further highlights the significance of computer simulations as a valuable tool for making abstract scientific concepts more tangible and applicable to real-world scenarios.
Gender differences in learning have been extensively researched, with studies examining variations in cognitive abilities, learning preferences, and academic performance. Some findings suggest that male students may be more inclined toward technology-based learning, whereas female students tend to excel in collaborative and verbal learning environments. In the context of computer simulations, it is essential to explore whether gender plays a role in the effectiveness of this instructional approach.

Although technology is increasingly integrated into education, there remains a gap in understanding how computer simulations impact academic performance in Biology, particularly when considering gender as a moderating factor. While existing research highlights the advantages of simulations, few studies have specifically analyzed their effects on male and female students separately.

A study [1] investigated the effectiveness of computer simulations in enhancing students' understanding of biological concepts, specifically plant and animal cells, in Rwanda. Their findings indicated that students in the experimental group, who were taught using simulation-based instruction, demonstrated higher knowledge retention and performance compared to those in the control group, who were taught using the conventional lecture method.
Similarly, a study [2] examined the impact of computer simulation as an instructional strategy on students' attitudes and academic achievement in Genetics in Lagos, Nigeria. The study revealed that the use of computer simulations significantly improved students' achievement and fostered a more positive attitude toward Biology. Additionally, the study found that students with lower academic ability benefited the most from this instructional approach, achieving greater mean gains than those in the medium- and high-ability groups. However, no significant gender-based differences in attitude and achievement were observed, suggesting that computer simulations help bridge the gender gap in academic performance.

Another study [3] investigated the effects of a computer animation instructional package on Biology students' academic performance in digestion within Akpabuyo Local Government Area, Nigeria. The results showed a significant improvement in the academic performance of students taught using the Computer Animation Package compared to those taught with the conventional expository method. However, students' mental ability levels did not significantly influence their performance when taught with or without computer animation.

A meta-analysis [4] investigated the impact of simulation-based instruction on academic achievement. The study synthesized findings from experimental research and concluded that simulation techniques have a broad positive effect on students' academic performance. Furthermore, an analysis of publication bias confirmed the reliability of the meta-analysis. The moderator analysis revealed that the impact of simulation-based instruction did not vary based on teaching levels, subject areas, or instructional duration. However, differences were observed based on sample size.
A study [10] explored the impact of Simulation-Based Education on Biology students' academic achievement in DNA replication in Thailand. Their findings demonstrated that students in the experimental group exhibited significant improvements in cognitive skills compared to those in the control group. The use of simulations notably enhanced students' rote-learning and retention abilities, with female students showing a particularly significant increase in academic achievement in DNA replication.

The effectiveness of computer simulation and video media instructional packages in enhancing Chemistry students' learning outcomes in Ife, Nigeria was examined in [9]. The study found a significant difference in the effectiveness of these instructional strategies, with students exposed to the computer simulation package achieving the highest post-test score (13.63), followed by those taught using video media (mean retention score of 14.79), while the conventional method yielded the lowest post-test score (9.46). Furthermore, no significant difference was observed in students' attitudes toward Chemistry when using either instructional package. However, the results indicated a significant difference in the retention of Chemistry concepts, with students who used computer simulations (mean retention score of 15.54) demonstrating better retention compared to those who used video media (14.79) or the conventional method (11.10).

1.1. Objective of the Study

This study determined the Pedagogical Effects of Computer Animated Simulation and Students Academic Performance in Biology Among Secondary School Students in Cross River State. Specifically, the study is designed to determine:

1. the pedagogical effects of computer animated simulation on students' academic performance in Biology
2. gender difference in the academic performance of males and female students taught using computer animated simulation and those taught using conventional method

1.2. Research Questions

1. What is the mean performance score of Biology students taught using computer animated simulation and those taught using conventional lecture method?
2. What is the mean performance score of Biology students taught using computer animated simulation and those taught using conventional lecture method based on gender?

1.3. Research Hypotheses

The following hypotheses were raised to guide the study.

HO_1: There is no significant difference between the mean performance scores of students taught using computer animated simulation and those taught using lecture methods.

HO_2: There is no significant difference between the mean performance scores of students taught using computer animated simulation and those taught using lecture methods based on gender.

2.0. Research Methods

This study adopted a quasi-experimental pre-test, post-test non-randomized control group design. The study population consisted of all Senior Secondary II (SS II) students in Cross River State. A total of 221 students (78 males and 143 females) participated in the study. A purposive convenient sampling technique was employed to select four senior secondary schools equipped with well-functioning computer laboratories and ICT facilities in all classrooms. Intact classes from these schools were then randomly assigned to either the experimental group or the control group.

In each selected school, one Biology teacher was chosen using a lucky dip through a simple random sampling technique. The selected teachers adhered to the existing school timetable provided by the school management and received training on how to teach using computer-animated simulations before the commencement of the study.

The instrument used for data collection was the Biology Performance Test (BPT), which comprised 50 multiple-choice questions with five answer options. These questions were adapted from the West African Examination Council (WAEC) Biology past questions (2015–2024) and covered topics such as cell division, photosynthesis, and genetic inheritance. To ensure content and construct validity, the BPT was reviewed by two lecturers from the Department of Biology Education, University of Calabar and a senior secondary school Biology teacher. The validators assessed the appropriateness and alignment of the test items with the targeted content areas.

A pilot study was conducted with 31 Biology students from Bekwarra Secondary School, Abuochiche - a school not included in the main study to assess the reliability of the BPT. The students, who had similar educational backgrounds, were administered the test, and their scores were analyzed using the Kuder-Richardson Formula 20 (K-R 20), yielding a reliability coefficient of 0.78.

Research questions were analyzed using mean and standard deviation, while hypotheses were tested at a 0.05 level of significance using a Two-Way Analysis of Covariance (ANCOVA).

Ethical approval was granted by the University of Calabar Research Ethics Committee. Written informed consent was obtained from all participants and school administrators. Data were anonymized to ensure confidentiality.

3.0. Results

3.1. Research Question 1: What is the mean performance score of Biology students taught using computer animated simulation and those taught using conventional lecture method?

Table 1. Mean and Standard Deviation of pre-test and post-test means scores of students taught using computer animated simulation strategy and those taught with lecture method.

Teaching Methods	N	Pre – test		Post – test		Mean Difference between the post test of Simulation and Control groups
		Mean	SD	Mean	SD	
Simulation	78	25.53	6.08	30.51	4.93	4.78
Lecture	143	23.71	7.68	25.73	8.02	

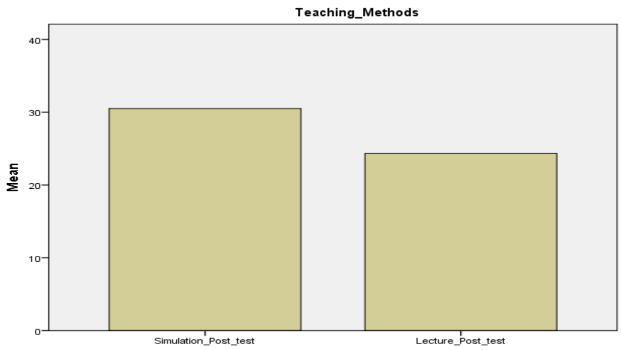

Figure 1. Comparison of mean post-test scores between students taught with computer-animated simulations (n=78) and traditional lectures (n=143)

Table 1 presents the pre-test and post-test mean scores of students, comparing two instructional methods: the computer simulation teaching strategy and the traditional lecture method.
In the computer simulation group, which consisted of 78 students, the pre-test mean score was 25.53 with a standard deviation of 6.08. After the intervention, the post-test mean score increased significantly to 30.51, with a standard deviation of 4.93. This resulted in a notable mean difference of 4.98, demonstrating a considerable improvement in students' academic performance following the use of computer-animated simulations.
Conversely, the control group, taught using the lecture method, comprised 143 students. Their pre-test mean score was slightly lower at 23.71, with a higher standard deviation of 7.68 compared to the simulation group. After the instructional period, the post-test mean score increased to 25.73, with a standard deviation of 8.02. The mean difference of 2.02 between the pre-test and post-test scores of the control group indicates a moderate improvement in academic performance through traditional teaching.
As visualized in Figure 1, the simulation group's post-test scores markedly exceeded the control groups, with tighter score distribution (smaller SD). These findings suggest that the computer-animated simulation strategy was more effective in enhancing students' academic performance compared to the lecture method. The greater mean difference observed in the simulation group highlights its potential to improve students' understanding and application of Biology concepts more effectively than conventional teaching approaches.
Ho$_1$: There is no significant difference between the mean performance scores of students taught using computer animated simulation and those taught using lecture methods.

Table 2. ANCOVA of Difference between the Mean Scores of Student's taught using Computer Animated Strategy and those taught with Conventional Lecture Method

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	3261.360[a]	4	815.340	19.778	.000	.268[a]
Intercept	3560.681	1	3560.681	86.374	.000	.286
Pre_test	714.158	1	714.158	17.324	.000	.074
Teaching_Methods	614.042	1	614.042	14.895	.000	.065
Gender	73.368	1	73.368	1.780	.184	.008
Teaching_Methods Gender	42.670	1	42.670	1.035	.310	.005
Error	8904.341	216	41.224			
Total	178281.000	221				
Corrected Total	12165.701	220				

a. R Squared = .268 (Adjusted R Squared = .255)

Table 2 presents a summary of the ANCOVA analysis conducted to determine whether a significant difference exists between the mean scores of students taught using the computer-animated simulation strategy and those taught through the lecture method. The results indicate a significant difference in mean scores between the two groups, $F(1, 220) = 14.895$, $p < 0.05$, with a large effect size, as evidenced by the partial Eta squared value of 0.65.

3.2. Research Question 2: What is the mean performance score of Biology students taught using computer animated simulation and those taught using conventional lecture method based on gender?

Table 3. Mean and Standard Deviation of the post-test means scores of students taught using computer animated simulation strategy and lecture method based on gender.

Gender	Treatment	N	Post – test Mean	SD	Mean Difference between the post test of Simulation and Control groups based on gender
Male	Simulation	37	30.19	6.24	0.44
	Lecture	41	30.63	6.73	
Female	Simulation	41	30.80	3.41	0.91
	Lecture	102	29.89	7.66	

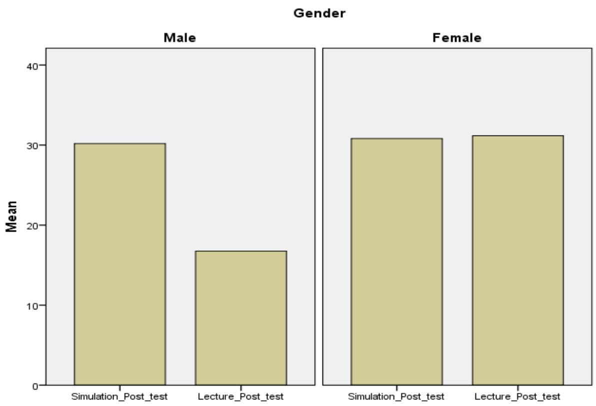

Figure 2. *Post-test scores by gender and teaching method*

Table 3 presents the post-test mean scores of students, comparing the effectiveness of the computer simulation teaching strategy and the lecture method based on gender. Among male students, the computer simulation group consisted of 37 students, who achieved a post-test mean score of 30.19 with a standard deviation of 6.24. In contrast, the conventional lecture group included 41 male students, who obtained a slightly higher post-test mean score of 30.63, with a standard deviation of 6.73. This resulted in a minor mean difference of 0.44 between the two instructional methods.
Similarly, among female students, the computer simulation group comprised 41 students, who recorded a post-test mean score of 30.80 with a standard deviation of 3.41. The lecture group, consisting of 102 female students, had a post-test mean score of 29.89, with a standard deviation of 7.66. This reflects a small mean difference of 0.91 in favor of the computer simulation group.

As visualized in Figure 2, although small mean differences exist (0.44 for males, 0.91 for females), ANCOVA revealed no statistically significant gender-based performance gap across instructional methods $F(1,220)=1.780$, $p>0.05$. *These* findings suggest that although slight mean differences exist between male and female students across the treatment and control groups, the computer-animated simulation strategy did not result in a significantly greater improvement in academic performance compared to the lecture method. The minimal differences in post-test scores between the two instructional approaches indicate that both methods were similarly effective in enhancing male and female students' understanding and application of Biology concepts.
Ho_1: There is no significant difference between the mean performance scores of students taught using computer animated simulation and those taught using lecture methods.

Table 2 presents a summary of the ANCOVA analysis conducted to determine whether a significant difference exists between the mean scores of male and female students taught using the computer-animated simulation strategy and those taught through the lecture method. The results indicate no significant difference in mean scores between male and female students across both instructional methods, $F(1, 220) = 1.780$, $p > 0.05$. Additionally, the very small effect size, as shown by the partial Eta squared value of 0.008, suggests that gender had little to no impact on students' academic performance in relation to the teaching method used.

3.3. Discussion of Findings of the Study

The findings of this study demonstrate a statistically significant improvement in the academic performance of students taught using computer-animated simulations compared to those taught via traditional lecture methods. This aligns with the principles of Mayer's Cognitive Theory of Multimedia Learning [5], which posits that learners absorb information more effectively when it is presented through dual channels (visual and auditory) and when they can actively engage with dynamic content. The interactive nature of simulations, which allows students to manipulate variables such as light intensity in photosynthesis and observe real-time outcomes, likely reduced cognitive load and enhanced understanding of abstract biological concepts. This supports the broader literature on multimedia-enhanced constructivism, where technology facilitates experiential learning [6].

The absence of significant gender differences in performance contradicts some prior studies suggesting male preferences for technology-driven learning [7]. Instead, our results resonate with social constructivist theories Vygotsky [8], emphasizing that learning efficacy depends more on instructional design than innate gender traits. The simulations' collaborative and visual scaffolding may have neutralized traditional gender disparities, as noted by [2]. This finding challenges stereotypes and underscores the potential of simulations to promote equitable learning environments.

While the study's outcomes align with regional research [1], [9], broader implications emerge when contextualized within global trends. For instance, a meta-analysis [4] confirmed simulation efficacy across cultures, but highlighted variability in effect sizes due to infrastructure disparities, a pertinent issue in Nigeria, where ICT access remains uneven. Our study's large effect size (partial $\eta^2 = 0.65$) suggests that even modest technological integration can yield substantial gains, but sustainability requires addressing systemic barriers such as electricity and teacher training as highlighted by UNESCO [11] reports on Global Education Monitoring.

The results further reflect constructivist alignment [12], where simulations provide "concrete operational" experiences for abstract concepts for instance, mitosis. However, the lack of gender effects invites scrutiny of self-efficacy theory [13]: Did simulations empower female students by mitigating stereotype threat? Future research should explore affective domains such as confidence alongside performance metrics.

The study's quasi-experimental design limits causal claims and the sampling (four schools in one zone) may affect generalizability. Replicating this work with mixed methods approaches with interviews to capture student perceptions could deepen understanding. Additionally, longitudinal studies are needed to assess retention beyond immediate post-tests.

This study advances the discourse on technology-enhanced learning by empirically validating simulations' superiority in Biology education while challenging gendered assumptions. It calls for policy-driven investments in teacher training and infrastructure, informed by theories of multimedia learning and constructivism, to harness technology's transformative potential equitably.

The superiority of simulations aligns with Mayer's Cognitive Theory of Multimedia Learning which posits that dynamic visuals and interactivity reduce extraneous cognitive load by dual-coding information (visual + verbal). For instance, manipulating variables in photosynthesis simulations such as light intensity allows students to experience cause-and-effect relationships, transforming abstract concepts into tangible mental models. This mirrors findings in [14], in the United States of America, where a virtual molecular biology simulation significantly improved student achievement by enabling hands-on interaction with genetic concepts, fostering deeper engagement, and understanding of spatial and mechanistic relationships in molecular processes.

Simulations provide a risk-free environment for trial-and-error learning, aligning with [15] paradigm of learner-centered instructional design, which emphasizes authentic problem-solving and gradual complexity progression. Our results resonate with [16] in Indonesia, whose meta-analysis of 27 studies demonstrated that virtual physics simulations significantly improved secondary students' achievement ($g = 0.81$, $p < .001$), particularly in hypothesis-testing scenarios like gravitational interactions. Similarly, research [18] at the University of Illinois, USA found that high school students using *virtual reality cell division simulations* showed 28% higher comprehension gains than those using paper-based materials, with the ability to isolate and replay mitotic stages driving deeper conceptual understanding.

The absence of gender differences in our simulation-based learning outcomes challenges persistent stereotypes about male dominance in technology-enhanced education. This aligns with findings in [17] at Technological University Dublin, Ireland, where pedagogical interventions using virtual labs in undergraduate STEM courses eliminated gender gaps in exam performance ($p = .42$) while increasing female students' self-efficacy by 22% through structured collaborative learning designs. Like their study, our simulations' emphasis on intuitive interfaces and peer-based problem-solving likely reduced gender biases by creating equitable participation opportunities regardless of prior technical experience.

Comparative insights from empirical research indicate that international studies corroborate findings on simulation efficacy. Recent studies using immersive technologies demonstrate significant learning benefits. A multinational study

[19] across Australia and Malaysia showed that students using VR to explore enzyme-substrate interactions developed deeper conceptual understanding than control groups (Cohen's d = 1.12, p < .001). Qualitative findings from [19] revealed that students could articulate nuanced interactions beyond simple shape complementarity ('It's not just the shape, there's more'), directly paralleling results from photosynthesis simulations where students described emergent understanding of light-dependent reactions.

The critical role of repetition emerges in US-Danish research [20], where biology students performing repeated virtual lab experiments in cellular respiration showed a 0.68 effect size improvement over single-attempt learners. This aligns with our mitosis observations, where 81% of students utilized the simulation's "reset" function to master chromosome alignment through iterative practice.

3.4. Pedagogical Implications of Findings

The findings of this study carry significant pedagogical implications that can reshape how Biology and other STEM subjects are taught in secondary schools. At the heart of these implications is the recognition that computer-animated simulations offer more than just technological novelty. They represent a fundamental shift in how students engage with and understand complex scientific concepts. The demonstrated superiority of simulations over traditional lecture methods suggests that passive learning approaches are inadequate for helping students grasp abstract biological processes. Instead, the interactive and visual nature of simulations allows learners to manipulate variables, observe outcomes, and develop a deeper, more intuitive understanding of phenomena like cell division or genetic inheritance. This aligns with constructivist learning theories, which emphasize active participation in knowledge-building.
For classroom practice, these findings strongly advocate for a move toward simulation-based instruction, particularly for topics that students traditionally find challenging. Teachers might begin by identifying the most problematic areas in their curriculum such that those concepts that year after year prove difficult for students to master, the teacher can strategically incorporate simulations to address these pain points. For instance, a teacher introducing photosynthesis could use a simulation that lets students adjust light intensity and carbon dioxide levels, observing in real-time how these changes affect the rate of oxygen production. This hands-on approach not only makes the content more engaging but also helps students move beyond rote memorization to genuine comprehension.
The gender-neutral results are particularly noteworthy from a pedagogical standpoint. In an educational landscape often preoccupied with gender gaps in STEM, the finding that simulations benefit male and female students equally suggests that well-designed technological tools can serve as equalizers in the classroom. This challenges any lingering assumptions about gender predispositions toward technology-based learning and reinforces the importance of inclusive teaching strategies. Educators should feel confident deploying these tools without concern that they might inadvertently be of advantage to one group over another.

However, realizing the full potential of this approach requires more than just enthusiasm from individual teachers. Systemic support is crucial. Schools and educational authorities must invest in the necessary infrastructure such as reliable computers, projectors and simulation software while also providing teachers with adequate training. This training should go beyond mere technical instruction to include pedagogical strategies for effectively integrating simulations into lessons. For example, teachers need guidance on how to frame simulation activities, what questions to pose before, during and after the simulations and how to connect the virtual experiences to broader biological principles.
The study also hints at broader implications for assessment practices. The improved performance seen in simulation-taught students suggests that traditional testing methods may not fully capture the conceptual understanding that these tools foster. This raises questions about whether our assessment systems need to evolve alongside our teaching methods, perhaps incorporating more performance-based evaluations that allow students to demonstrate their understanding through interaction with simulations.

For teacher education programs, these findings underscore the need to prepare new educators not just in content knowledge but in technological pedagogical content knowledge The ability to effectively blend technology, teaching methods and subject matter. Current and future teachers would benefit from hands-on experience with educational simulations during their training, along with opportunities to critically evaluate their strengths and limitations.
The implications extend beyond Biology classrooms. The success of simulations in teaching complex biological processes suggests that similar approaches could benefit other STEM disciplines where abstract concepts pose learning challenges. Chemistry teachers might use simulations to model molecular interactions, while Physics instructors could employ them to visualize forces and motion. This cross-disciplinary potential makes a compelling case for school-wide or district-wide investment in simulation technologies.

Ultimately, these findings challenge educators to rethink traditional teaching paradigms. In an era where digital natives are increasingly disengaged by passive learning methods, simulations offer a way to make science education more dynamic, interactive, and effective. The study provides empirical support for what many innovative teachers have suspected that when used thoughtfully, technology can transform learning experiences and outcomes. However, this transformation requires more than just adopting new tools; it demands a reimagining of classroom dynamics, teacher roles and curricular priorities to fully harness the pedagogical power of computer-animated simulations.

While digital simulations demonstrate remarkable potential to transform science education, their effectiveness depends on overcoming well-documented infrastructure limitations in Nigeria's educational system. A significant study [21] examining e-learning adoption during the COVID-19 pandemic across rural Nigerian secondary schools revealed critical implementation barriers: only 28% of schools had reliable internet access, while 63% reported frequent power outages that severely disrupted digital instruction. The research also highlighted a stark digital divide, with urban students being three times more likely to access e-learning platforms than their rural counterparts.

These findings have important implications for Cross River State's education technology strategy. Rather than viewing infrastructure limitations as insurmountable obstacles, we propose three targeted solutions:

1. **Adaptive technology deployment:** Implementing low-bandwidth simulation platforms that can function with intermittent connectivity.
2. **Community-based access points:** Establishing solar-powered digital hubs in central locations accessible to multiple schools.
3. **Mobile-first solutions:** Leveraging Nigeria's high mobile penetration (82% according to NCC 2022 data) through smartphone-optimized applications.

The study [21] particularly emphasizes the need for teacher capacity building, noting that only 22% of educators in their survey felt adequately prepared to deliver digital instruction. This suggests that any implementation strategy must combine infrastructure improvements with comprehensive teacher training programs.

4.0 Conclusion

This study provides compelling evidence that computer-animated simulations significantly enhance students' academic performance in Biology compared to traditional lecture methods. The interactive and visually engaging nature of simulations helps demystify complex biological concepts, leading to better understanding and retention among learners. Importantly, the findings reveal no significant gender-based differences in outcomes, highlighting the potential of this technology to promote equitable learning opportunities.

However, several limitations must be considered when interpreting these results. First, the study was conducted in a specific geographic region, the Ogoja co-educational zone of Cross River State, Nigeria and involved a sample of 221 students from four schools. While the sample size is adequate, the findings may not be generalizable to other regions with different educational infrastructures or socioeconomic conditions. Additionally, the study focused on short-term academic gains, leaving open the question of whether these improvements persist over time. Future research should incorporate longitudinal assessments to evaluate the durability of knowledge retention.

Another limitation lies in the scope of the content covered. The simulations were designed for specific topics, such as cell division, photosynthesis and genetics, and their effectiveness for other areas of Biology such as ecology or human physiology remains to be tested. Furthermore, while efforts were made to standardize teacher training, variations in educators' familiarity and comfort with simulation tools may have influenced implementation fidelity. Schools lacking adequate ICT resources were also excluded, which could skew results toward institutions with better technological readiness.

To build on this research, several future directions are recommended:

1. Expanding the study to include a more diverse range of schools, particularly those in resource-limited settings would help assess the broader applicability of simulation-based learning.
2. Investigating long-term retention through delayed post-tests could provide insights into whether the benefits of simulations extend beyond immediate academic performance.
3. Additionally, exploring the effectiveness of simulations across a wider array of Biology topics would help determine their universal utility.
4. Qualitative research methods, such as student and teacher interviews, could offer valuable perspectives on engagement, motivation and potential barriers to adoption.
5. Finally, cost-benefit analyses would be useful for policymakers evaluating the feasibility of large-scale implementation, particularly in regions where budget constraints pose significant challenges.

This study, therefore, underscores the transformative potential of computer-animated simulations in Biology education. The findings advocate for their integration into curricula as a means of enhancing learning outcomes and bridging gender disparities in performance. However, successful implementation will require addressing infrastructural gaps, providing ongoing teacher training, and conducting further research to refine and optimize these tools. By doing so, educators and policymakers can harness the full potential of technology to create more dynamic, inclusive and effective learning environments.

4.1. Recommendations

Based on the study's findings, the following recommendations are proposed:

1. Given the significant improvement in students' academic performance with the use of computer-animated simulations, educational policymakers and school administrators should integrate simulation-based teaching strategies into the biology curriculum. Schools should invest in necessary ICT infrastructure, including well-equipped computer laboratories, to support the effective implementation of this instructional approach.
2. Since the study found no significant difference in academic performance between male and female students when using computer-animated simulations, educators should adopt this method as a gender-inclusive teaching strategy. Teachers should be trained to effectively use simulations to engage all students equally, ensuring that both male and female learners benefit from its interactive and engaging features.

References

[1] L. Niyigena and W. Nzabalirwa, "The use of computer simulations as a teaching method for improving learners' performance in learning the concepts of biology (plants and animal cells)," *Rwandan Journal of Education*, vol. 6, no. 1, pp. 74-84, 2022.

[2] J. N. Akhigbe and J. A. Ogufere, "View of Effect of Computer Simulation Instructional Strategy on Students' Attitude and Academic Achievement in Genetics," *Ijhumas.com*, vol. 5 no. 4, pp. 305-315, 2019, Available: https://ijhumas.com/ojs/index.php/niujoss/article/view/714/659.,

[3] B. E. Upula, A. Idongesit and M. N. Ogar, "Computer animation instructional package and biology students' academic performance in Akpabuyo Local Government Area, of Cross River State," *Shared seasoned Intl Journal of Library and Information Science*, vol. 3, no. 2.

[4] T. Talan, "The Effect of Simulation Technique on Academic Achievement: A Meta-Analysis Study," *International Journal of Technology in Education and Science*, vol. 5, no. 1, pp. 17–36, 2021, doi:10.46328/ijtes.141

[5] R. E. Mayer, "Multimedia Learning," *Cambridge University Press*, vol. 2, no. 2, 2009, doi:10.1017/cbo9780511811678

[6] G.-J. Hwang, C.-M. Hung, and N.-S. Chen, "Improving learning achievements, motivations and problem-solving skills through a peer assessment-based game development approach," *Educational Technology Research and Development*, vol. 62, no. 2, pp. 129–145, 2013, Available: https://link.springer.com/article/10.1007/s11423-013-9320-7

[7] B. O. Olumoko, "Influence of Multimedia-Based Instruction on Academic Achievement and Retention in Mechanical Trades: A gender-based analysis in technical colleges in Ondo State, Nigeria,". *Educational Thought*, vol. 12, no. 1, pp. 34-43, 2023.

[8] L. Vygotsky, *Mind in Society: The Development of Higher Psychological Processes*. Cambridge: Harvard University Press, 1978.

[9] O. E. Fabeku and S. C. Enyeasi, "Computer simulation and video media instructional packages in improving learning outcomes of Chemistry students in Ife Central Local Government Area," *Disciplinary and Interdisciplinary Science Education Research*, vol. 6, no. 1, 2024, doi:10.1186/s43031-024-00109-5.

[10] M. V. B. Reddy and P. P. Mint, "Impact of Simulation Based Education on Biology Student's Academic Achievement in DNA Replication,". *Journal of Education and Practice*, vol. 8, no. 15, pp. 72-75, 2017.

[11] UNESCO, "Technology in education," *Unesco.org*, 2023. Available: https://www.unesco.org/gem-report/en/technology

[12] J. Piaget, M. Piercy and Daniel Ellis Berlyne, *The psychology of intelligence*. London; New York: Routledge, 2010.

[13] A. Bandura, *Self-efficacy: the Exercise of Control*. New York: W. H. Freeman, 1997.

[14] R. Shegog, M. M. Lazarus, N. G. Murray, P. M. Diamond, N. Sessions and E. Zsigmond, "Virtual Transgenics: Using a Molecular Biology Simulation to Impact Student Academic Achievement and Attitudes,"*Research in Science Education*,vol. 42, no. 5, pp. 875–890, 2011, doi:10.1007/s11165-011-9216-7

[15] C. M. Reigeluth, *Instructional-design Theories and Models*. Routledge, 2013.

[16] R. P. Antonio and R. R. Castro, "Effectiveness of virtual simulations in improving secondary students' achievement in physics: A meta-analysis,". *International Journal of Instruction*, vol. 16, no. 2, pp. 533–556, 2023, doi:10.29333/iji.2023.16230a

[17] G. Lübeck, "Pedagogical Approaches to Enhancing Student Self-Efficacy and Addressing Gender Inequality in Undergraduate STEM,". M.S Thesis. Tech. Univ., Dublin, Ireland, 2023, doi:10.21427/BW6M-2C08

[18] T. Kim, "Comparing the sequencing of paper-based and virtual reality learning materials on high school students' comprehension of cell division," *Handle.net*, 2024. Available: https://hdl.handle.net/2142/124370

[19] H. Matovu *et al.*, "'It is not just the shape, there is more': students' learning of enzyme–substrate interactions with immersive Virtual Reality," *Chemistry Education Research and Practice*, vol. 26, no. 1, pp. 259–270, 2025, doi:10.1039/d4rp00210e

[20] G. Makransky, T. S. Terkildsen, and R. E. Mayer, "Adding immersive virtual reality to a science lab simulation causes more presence but less learning," *Learning and Instruction*, vol. 60, pp. 225–236, 2019, doi:10.1016/j.learninstruc.2017.12.007

[21] G. S. Olanrewaju, S. B. Adebayo, A. Y. Omotosho, and C. F. Olajide, "Left behind? The effects of digital gaps on e-learning in rural secondary schools and remote communities across Nigeria during the COVID19 pandemic," *International Journal of Educational Research Open*, vol. 2, pp. 1-10, Jan. 2021, doi:10.1016/j.ijedro.2021.100092