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FROM ABSTRACTION TO UNDERSTANDING: THE IMPACT OF COMPUTER SIMULATIONS ON GENETICS LEARNING AND STUDENT PERCEPTIONS IN NZEMA EAST MUNICIPALITY

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Abstract:
Genetics is a challenging area of senior high school biology due to its abstract molecular concepts, often difficult for students to grasp through conventional teaching. This study examined the effectiveness of computer simulation–based instruction in improving achievement and perceptions of genetics using a quasi-experimental one-group pretest–posttest design within a mixed-methods framework. The sample included 120 Form

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Three Biology students from three senior high schools in Nzema East Municipality. Data were collected using the Students' Knowledge in Genetics Test (SKGT) and Students' Achievement in Genetics Test (SAGT), both showing good reliability (α = 0.79 and 0.84; κ = 0.75 and 0.64). Wilcoxon Signed Rank Test results indicated significant improvement, with mean scores rising from 8.80 to 23.30 (z = 9.52, p = 0.001, r = 0.87). Interviews with 15 students revealed positive perceptions, including enhanced clarity, motivation, retention, engagement, and real-life application. The study concludes that computer simulations significantly enhance performance and attitudes, recommending curriculum integration and teacher training.

Keywords: computer simulations; genetics education; quasi-experimental design; student perceptions; Nzema East Municipality

1. Background to the Study

Teaching genetics at the Senior High School (SHS) level remains a difficult task because many of its core concepts, such as DNA replication, inheritance, meiosis, mitosis, cell division and protein synthesis, are highly abstract and complex. Traditional methods that rely mainly on lectures, chalkboard diagrams, discussions, and occasional laboratory demonstrations often prove insufficient (Reddi *et al.*, 2025). These approaches rarely succeed in connecting theoretical explanations with students' conceptual understanding, leading instead to rote memorisation or surface-level learning (Byukusenge, 2024; Deep *et al.*, 2020).

To address these challenges, educators have increasingly turned to computer simulations as innovative tools for teaching science. Simulations transform abstract biological processes into interactive and visual experiences. They give learners the chance to manipulate variables, test hypotheses, observe real-time outcomes, and receive instant feedback, all of which encourage inquiry-based learning and deeper comprehension (Liu *et al.*, 2023; Kong *et al.*, 2023). The shift toward digital instruction during the COVID-19 pandemic further accelerated their adoption, drawing attention to the role of students' perceptions in shaping how effective these tools can be for learning (Elendu *et al.*, 2024; Singh-Pillay, 2024).

Research in secondary biology classrooms reinforces these benefits. Studies show that simulations, especially when used in blended or flipped learning contexts, improve students' motivation, knowledge retention, and academic achievement while helping to overcome challenges such as limited laboratory access (Nsabayezu *et al.*, 2025; Reen *et al.*, 2024). Collectively, these findings highlight simulations as a practical and effective strategy for strengthening the teaching and learning of genetics at the SHS level, enhancing both student engagement and conceptual mastery.

2. Problem Statement

Although research evidence suggests that computer simulations can enhance students' learning of genetics, their success often depends on how learners perceive them in practice. Students' views on the usefulness, relevance, and ease of integration of simulations into their learning environment can strongly influence outcomes. Some studies report that learners find simulations helpful for deepening understanding and encouraging active participation, while others highlight challenges linked to poor digital infrastructure, limited teacher expertise, or weak alignment with curriculum requirements (Hertel & Millis, 2023, p. 45; Byukusenge, 2023).

These contrasting experiences highlight the importance of exploring Senior High School (SHS) students' perceptions of simulation-based instruction, particularly in settings where infrastructural gaps and varying levels of teacher preparedness may influence implementation. Without such insights, schools risk underusing or misapplying simulations, which reduces their potential impact on genetics education. A systematic investigation of students' attitudes is therefore essential not only to guide teacher training and curriculum design, but also to ensure that simulation-based approaches are adopted fairly and effectively at the senior high school level.

2.1 Purpose of the Study

The purpose of this study is to investigate the role of computer simulation-based instruction in enhancing the teaching and learning of genetics at the senior high school level. Specifically, the study aims to assess the effectiveness of simulation-based strategies in enhancing students' academic performance in genetics, a subject widely regarded as abstract and conceptually demanding. In addition, the study aims to explore students' perceptions of simulation-based learning experiences, focusing on how they view its relevance, accessibility, and contribution to their understanding of genetics concepts. By addressing both performance outcomes and learner perceptions, the study provides a comprehensive understanding of the pedagogical value of computer simulations, offering insights that can inform instructional practice, curriculum design, and teacher professional development in science education.

2.2 Research Questions

1) What is the effect of computer simulation-based instruction on students' performance in genetics?
2) What are students' perceptions of the computer simulation-based instruction?

2.3 Limitations of the Study

This study is not without limitations. The use of a quasi-experimental one-group pretest–posttest design limited the ability to draw strong causal inferences, since the absence of a control group means that other external factors may have contributed to the observed improvement in performance. In addition, the research was carried out in three senior high schools within a single municipality, which restricts the extent to which the findings can be generalised to other geographical contexts or school settings. Furthermore, the intervention focused on specific aspects of genetics such as DNA replication and protein synthesis, making it difficult to assume that similar outcomes would occur for other areas of biology. Finally, the study was implemented under conditions where technological resources and teacher readiness were relatively well managed; in less resourced or differently structured environments, the outcomes might vary. Despite these limitations, the study provides strong evidence that computer simulations can significantly improve both academic achievement and learner perceptions in genetics, and it highlights practical implications for curriculum planning and teacher professional development.

3. Literature Review

3.1 Theoretical Review

This study is underpinned by constructivist learning theory, which emphasises that learners actively build knowledge through interaction with their environment rather than passively receiving information. Piaget's view of constructivism highlights the importance of cognitive development through assimilation and accommodation, where learners integrate new experiences into prior knowledge structures. In the context of genetics instruction, computer simulations provide opportunities for students to test ideas, manipulate variables, and reconcile misconceptions, thereby supporting the construction of more robust mental models (Jalmo & Suwandi, 2018). Similarly, Vygotsky's sociocultural perspective underscores the role of social interaction and scaffolding in knowledge construction. Simulation-based instruction often involves collaboration, peer discussion, and teacher guidance, which collectively situate learning within the learner's zone of proximal development (Clapper, 2015).

Another relevant perspective is experiential and inquiry-based learning theory, which argues that learning is most effective when students engage in active experimentation and reflection. Simulations replicate real-world scenarios that allow learners to explore abstract genetic processes such as inheritance and molecular interactions in a safe, repeatable, and interactive environment. Through experimentation, students can ask questions, predict outcomes, and immediately observe consequences, which fosters critical thinking and deeper understanding (Sasson *et al.*, 2018). Moreover, inquiry-based approaches align with the design of many modern simulation tools that emphasize exploration, discovery, and problem-solving rather than rote memorization.

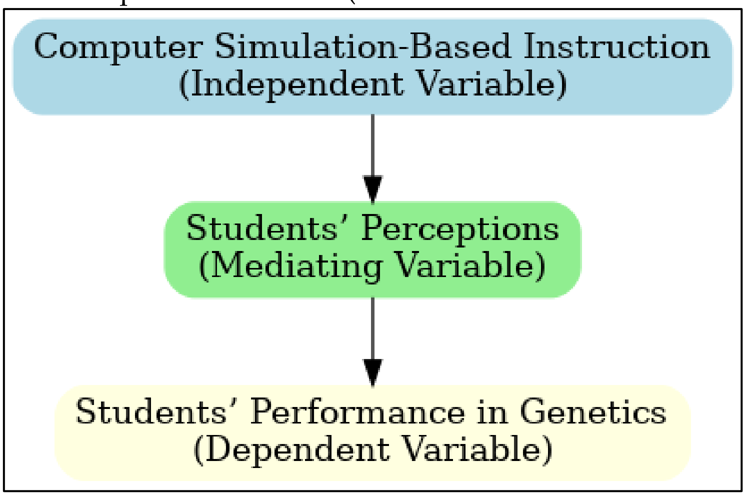
Integrating these theoretical perspectives, simulation-based instruction in genetics not only provides visual and interactive experiences but also positions students as active participants in meaning-making. Constructivism justifies the individualised and collaborative aspects of simulation learning, while experiential and inquiry-based theories validate the hands-on and exploratory nature of the approach. Together, these theories offer a strong rationale for examining both the effectiveness of simulation in enhancing academic performance and the perceptions students hold about this instructional strategy in the SHS context.

3.2 Conceptual Framework

This study is guided by a conceptual framework that positions students' perceptions as a mediating variable in the relationship between computer simulation–based instruction and academic performance in genetics. Computer simulations are expected to improve students' learning by making abstract genetic concepts more concrete, interactive, and engaging. However, the extent to which these benefits translate into higher performance is influenced by how students perceive the instructional strategy. Positive perceptions, such as finding simulations engaging, relevant, and easy to use, can enhance motivation, participation, and conceptual understanding, which in turn improve performance outcomes. Conversely, negative perceptions related to usability, accessibility, or instructional value may reduce the effectiveness of simulations, leading to limited learning gains.

Thus, while computer simulation-based instruction serves as the independent variable and students' performance in genetics represents the dependent variable, perception functions as a mediating factor that shapes the strength and direction of this relationship. By examining perception as a mediator, the framework captures the complex interplay between instructional innovation, learner attitudes, and academic achievement, providing insights for more effective integration of simulations in science education.

Figure 1: Conceptual framework (Source: Researcher's construct, 2025)



3.3 Computer Simulations and Genetics Learning

A growing body of research has investigated the impact of computer simulations on students' understanding of genetics, highlighting their potential to address learning difficulties commonly associated with abstract biological concepts. Genetics often involves processes that are not directly observable, such as gene expression, meiosis, and inheritance patterns. Traditional methods, which rely heavily on chalk-and-talk strategies, may not adequately convey the dynamic and microscopic nature of these concepts. Computer simulations, however, provide visual and interactive experiences that can enhance conceptual clarity.

For instance, a study by Darrah *et al.* (2014) found that high school students who learned genetics through simulations showed significantly higher gains in conceptual understanding compared to those who received textbook-based instruction. The researchers concluded that the visual and interactive nature of simulations helped students make meaningful connections between genetic processes and real-world phenomena. Similarly, Gelbart and Yarden (2019) emphasised that simulations enabled learners to bridge the gap between symbolic representations and the actual biological mechanisms involved in genetic inheritance, making learning more engaging and effective.

In the African context, Appiah and Essiam (2022) conducted a quasi-experimental study in Ghana to compare the performance of students taught genetics using computer simulations with those taught using traditional methods. The results indicated that students in the simulation group scored significantly higher on post-tests and demonstrated better retention of knowledge. The authors argued that simulations helped demystify complex genetic processes such as Mendelian crosses and DNA replication, which are usually abstract when taught theoretically.

Another relevant study by Chang *et al.* (2020) involved the use of interactive genetics simulations among secondary school students in Taiwan. Their findings revealed that students not only improved in academic performance but also exhibited higher levels of scientific reasoning and inquiry skills. The authors attributed these outcomes to the simulations' ability to present learners with multiple representations, immediate feedback, and the opportunity to explore biological phenomena at their own pace.

While the majority of existing studies affirm the benefits of simulations in genetics education, few have focused specifically on their use in rural or under-resourced settings such as Nzema East Municipality. Additionally, most existing research does not explore how simulations compare to conventional teaching methods in these contexts. As such, this study aims to fill that gap by evaluating how computer simulations influence students' understanding of genetics in a typical Ghanaian senior high school environment.

3.4 Students' Perceptions of Learning Genetics at the SHS Level

Students' perceptions of genetics at the senior high school level are shaped by a combination of curiosity, perceived difficulty, and instructional exposure. Research consistently shows that many learners find genetics both interesting and intimidating due to its abstract concepts and technical language (Chu, 2008). In a recent study, Mills Shaw *et al.* (2008) reported that while students demonstrated some enthusiasm for genetics, the majority held misconceptions about gene function and inheritance, which negatively influenced their confidence and overall perception of the subject. Similarly, Duncan and Reiser (2007) found that students often describe genetics as one of the most difficult aspects of biology, a view attributed to its heavy reliance on abstract reasoning rather than observable phenomena.

Instructional approaches strongly influence how students perceive genetics. Studies comparing conventional lecture-based methods with learner-centred strategies, such as flipped classrooms and gamified instruction, demonstrate that students taught with active-learning techniques report more positive attitudes and greater perceived relevance of genetics to their lives (Pretorius, 2023). In the same vein, Himschoot (2012) observed that learners' interest in genetics increased when instruction emphasised everyday applications and biotechnology, suggesting that contextualised teaching shapes perception by linking abstract concepts to real-world implications.

The integration of digital tools has also been found to play a crucial role in shaping perceptions. For instance, Fabeku and Enyeasi (2024) demonstrated that students exposed to computer simulations and video-based instructional packages reported greater engagement and improved attitudes toward abstract science concepts compared to peers in traditional classrooms. Similarly, studies conducted in African contexts show that computer simulations enhance learners' interest and perceptions by making invisible processes, such as molecular interactions, more tangible and interactive (Nkosi, 2019). However, O'Connor *et al.* (2014) emphasised that technology integration must be carefully scaffolded; without appropriate teacher guidance, students may perceive digital resources as overwhelming or disconnected from curriculum objectives.

Persistent misconceptions also act as barriers to positive perception. Silumesi (2022) highlighted that students often confuse gene, allele, and chromosome concepts, leading to frustration and the belief that genetics is inaccessible. These misconceptions are reinforced by inadequate teaching resources and the abstract nature of molecular processes (Adelana *et al.*, 2024). Scholars argue that addressing such misconceptions requires explicit diagnostic teaching strategies and conceptual change approaches, which help students perceive genetics as learnable rather than overly complex (Gottheiner & Siegel, 2012).

Structural and contextual factors further shape perception. Resource constraints, such as limited laboratory facilities and poor access to digital tools, often cause students to perceive genetics as an abstract, rote-learning subject rather than an applied science (Adelana *et al.*, 2024). In Nigeria, Fabeku *et al.* (2024) found that students in under-resourced schools expressed lower confidence in learning genetics despite their curiosity, indicating that perception is mediated by the availability of supportive infrastructure and teacher preparedness.

While some studies note gender and prior achievement as potential moderators, evidence remains mixed. Huang (2013) observed no significant gender differences in overall attitudes toward genetics, although cultural contexts may influence self-efficacy differently for boys and girls. Lower-achieving students, however, appear to benefit more perceptually from interactive, scaffolded instructional designs, often reporting improved attitudes and confidence compared to their higher-achieving peers (Ferguson, 2012).

Overall, the reviewed studies reveal that students' perceptions of genetics at SHS are shaped by misconceptions, instructional approaches, technology integration, and contextual factors. While learners are curious about genetics, they often view it as difficult and abstract unless supported by engaging pedagogies and adequate resources. This suggests the need for further research in underexplored contexts, particularly in West Africa, Ghana, to examine how simulation-based instruction can reshape perceptions by making genetics more accessible and relevant.

4. Methodology

4.1 Research Paradigm

In simple terms, a research paradigm refers to the underlying philosophical or theoretical foundation upon which a study is based. It is often referred to as a research philosophy. The term "paradigm" was first introduced into academic discourse by American philosopher Thomas Kuhn in 1962, who used it to describe a distinctive way of thinking within scientific inquiry (Orman, 2016). In the field of educational research, the term is commonly used to represent a researcher's worldview, an overarching perspective that influences how knowledge is conceptualised and how data are interpreted (Mackenzie & Knipe, 2006).

This research is guided by the pragmatic paradigm, a philosophical approach that prioritises the use of multiple methods to investigate complex real-world problems. As explained by Tashakkori and Teddlie (2010), pragmatism advocates for methodological flexibility and is primarily concerned with what works best in addressing specific research questions, rather than adhering strictly to any one philosophical tradition. The pragmatic worldview is particularly well-suited to educational research that seeks to understand both the measurable outcomes of an intervention and the subjective experiences of participants.

4.2 Research Design

The study employed a quasi-experimental one-group pretest–posttest design situated within an embedded mixed-methods framework. This design was deemed appropriate because it allowed the researcher to determine changes in students' academic performance after exposure to computer simulation–based instruction, while simultaneously exploring their perceptions of the approach. In this model, a single group of students was assessed before the intervention using the Students' Knowledge in Genetics Test (SKGT) and reassessed after the intervention using the Students' Achievement in Genetics Test (SAGT). The absence of a control group limits causal claims but provides a practical means of evaluating the instructional strategy in real classroom settings.

The qualitative component was embedded to enrich the quantitative findings and provide explanatory insights. Semi-structured interviews were conducted with a subsample of 15 students systematically selected from the main group. Class registers served as the sampling frame, and every nth student was chosen to ensure representation across the group. This procedure ensured that perspectives from students with different performance levels and backgrounds were included, thereby strengthening the validity of the qualitative strand.

This combined approach was selected because genetics is widely recognised as abstract and conceptually demanding at the senior high school level. Addressing both measurable learning outcomes and subjective learner perceptions provides a more holistic understanding of the effectiveness of computer simulation–based pedagogy. Embedding qualitative insights within a predominantly quantitative design also enhances interpretation and aligns with current recommendations in science education research to use multiple forms of evidence when assessing innovative instructional strategies (Borrego & Henderson, 2014).

4.3 Sampling Procedure

Sampling is a fundamental aspect of research, involving the selection of a portion of a population to participate in a study, to draw conclusions that can be generalised to the entire group. According to Weyant (2022), sampling is crucial when it is impractical to study every member of a population due to constraints such as time, accessibility, or cost. In the context of educational research, sampling enhances the manageability of data collection while maintaining the representativeness of the study (Omona, 2013). Researchers must therefore adopt sampling strategies that are not only practical but also methodologically sound.

A multistage sampling procedure was employed to ensure the suitability and representativeness of the study sample. First, purposive sampling was used to select three public senior high schools in Nzema East Municipality, Kwame Nkrumah SHS, Axim Girls' SHS, and Gwiraman SHS based on their offering of Biology and accessibility. In the second stage, all third-year Biology students in the selected schools were purposively included, as the study focused on genetics, a core Biology topic. In the third stage, simple random sampling was used to select two intact classes from each school, assigning one to the experimental group and the other to the control group, with classification based on pre-test results from the Students' Knowledge in Genetics Test (SKGT). Finally, systematic random sampling was conducted to select 5 students from each experimental group for interviews, using class registers at different intervals across schools, ensuring balanced representation for the qualitative strand of the study.

Altogether, the sample consisted of 120 senior high school students drawn from three intact classes across the three selected schools, with three classes assigned to the experimental condition and the other three to the control condition. Among the total participants, 86 were females, accounting for 71.67%, while 34 were males, representing 28.33%. The arrangement of participants within the study sample is outlined in Table 3.1 below.

Table 1: Summary of Participants in the Study

School	Class	Boys (%)	Girls (%)	Total
Kwame Nkrumah Sen High Sch.	3SC B (Exp. Group 1)	14 (45.16%)	17 (54.84%)	31
Axim Girls Senior High School	3H E1 (Exp. Group 2)		57 (100.00%	57
Gwiraman S.H.S	3SC (Exp Group 3)	20 (62.50%)	12 (37.50%)	32
Total		34 (28.33%)	86 (71.67%)	120

4.4 Instruments

For this study, a mixed-method approach was adopted, necessitating the use of both quantitative and qualitative instruments. The quantitative data were collected using two researcher-developed test instruments: The Students' Knowledge in Genetics Test (SKGT) and the Students' Achievement in Genetics Test (SAGT). The SKGT served as a pre-test to assess students' prior understanding of genetics concepts before the intervention. The SAGT was administered as a post-test to measure the academic gains made by students after exposure to either the computer simulation instructional strategy or the conventional teaching method.

Each test consisted of 10 multiple-choice items, each with four answer options, and five structured response questions aimed at assessing comprehension, application, and interpretation of genetics concepts such as DNA and RNA structure, DNA replication, and protein synthesis. The instruments were developed in alignment with the SHS Biology syllabus and reviewed by subject experts to ensure content validity.

In addition to the test instruments, a semi-structured focus group interview guide was developed to collect qualitative data from selected students in the experimental group. The interviews aimed to explore students' perceptions of the computer simulations instructional approach, including its usefulness, clarity, and effect on their motivation and understanding. This approach aligns with the recommendations of Patton *et al.* (2015), who advocate for the use of open-ended qualitative instruments to complement quantitative findings in mixed-methods research. Overall, the instruments used were chosen to comprehensively address the research objectives and ensure that both performance outcomes and learner experiences were captured.

4.5 Validity and Reliability of Instruments

To ensure content validity, the Students' Knowledge in Genetics Test (SKGT) and the Students' Achievement in Genetics Test (SAGT), which served as pre-test and post-test, respectively, were reviewed by a senior lecturer, the researcher's supervisors, and three experienced SHS Biology teachers. The reviewers evaluated the items for clarity, appropriateness of language, relevance to the genetics curriculum, and alignment with the research objectives. Similarly, the semi-structured interview guide was examined by the same panel of experts to confirm that its questions were well-worded, aligned with the study objectives, and capable of eliciting meaningful insights from participants.

The instruments were further pre-tested at Baidoo Bonsu Senior High Technical School using 42 third-year science students offering Biology, who shared similar characteristics with the target population but were excluded from the main study. This pre-testing provided feedback on the clarity, reliability, and suitability of both the test instruments and the interview guide, consistent with Hertzog's (2008) recommendation of 10–40 participants for pilot studies.

For reliability, internal consistency of the SKGT and SAGT objective items was measured using Cronbach's alpha, which produced values of α = 0.79 and α = 0.84, respectively. According to George and Mallery (2018), values above 0.70 are acceptable, while those exceeding 0.80 indicate good reliability. For the essay items, inter-rater reliability was assessed using Cohen's Kappa, yielding $\kappa = 0.75$ for SKGT and $\kappa = 0.64$ for SAGT. Based on Landis and Koch's (1977) interpretive scale, these results reflect substantial to almost perfect agreement, ensuring that scoring was consistent across evaluators.

Together, these processes confirmed that the instruments, the SKGT, SAGT, and the semi-structured interview guide were valid, reliable, and appropriate for generating credible data to address the research objectives.

4.6 Data Collection Procedure

The data collection process was carefully planned and executed in phases to ensure systematic administration of the research instruments and alignment with the study's objectives. The activities were carried out across the selected senior high schools in the Nzema East Municipality following ethical approval and formal authorisation from the district director and the various headmasters. The procedure involved seeking institutional permissions, familiarising participants with the study, administering pre- and post-test instruments, and conducting interviews with selected students.

The intervention phase spanned seven weeks across three senior high schools, Kwame Nkrumah SHS, Axim Girls' SHS, and Gwiraman SHS and aimed to evaluate the effectiveness of computer simulations in improving Form Three Biology students' understanding and perception of genetics. To minimise the Hawthorne effect and avoid cross-school influence, the intervention was implemented sequentially in each school. An unplanned one-week extension occurred at Gwiraman SHS due to an athletics competition, but the planned lessons were completed. Students in the experimental groups received curriculum-based genetics instruction covering DNA and RNA structure, DNA replication, and protein synthesis through interactive computer simulations, guiding questions, and group discussions. Consistency was ensured by using identical instructional materials, software, sequences, and assessments across all sites.

4.7 Implementation of the Simulation-Based Lesson on DNA Replication

4.7.1 Defining Learning Objectives

At the beginning of the lesson, clear objectives were established to guide both teaching and learning. By the end of the 70-minute session, students were expected to describe the structure of DNA, identify the roles of key enzymes involved in replication (helicase, polymerase, ligase), illustrate the steps of the replication process, and explain the semi-conservative nature of DNA replication using a simulation. These objectives provided a roadmap for both instruction and assessment.

4.7.2 Selecting an Appropriate Simulation

BiomanBio was selected as the main simulation tool because of its curriculum alignment, interactive features, and capacity to model complex molecular events in an engaging manner. Its animations, manipulatives, and built-in quizzes made it particularly effective for visualising enzyme activity, strand separation, and complementary base pairing during DNA replication.

4.7.3 Providing Pre-Simulation Instruction

To activate prior knowledge, the teacher reviewed earlier concepts such as the nucleus as the storage site of genetic material and the basic structure of the DNA double helix. Guiding questions like "Why must DNA be replicated before cell division?" were posed to elicit responses. The teacher then used a short animation from the simulation platform to introduce the concept of replication, clarified terms such as "leading strand" and "lagging strand," and demonstrated how to navigate BiomanBio. This ensured students were prepared for interactive exploration.

4.7.4 Guiding Student Exploration

Students engaged directly with the simulation in three phases. First, they visualised the unwinding of the DNA double helix by helicase. Second, they manipulated models to observe how DNA polymerase adds complementary nucleotides according to base-pairing rules (A–T, C–G). Third, they explored how ligase connects Okazaki fragments on the lagging strand. At each phase, the teacher facilitated learning through probing questions, encouraged predictions about strand synthesis, and required students to justify their reasoning while responding to embedded quizzes.

4.7.5 Facilitating Debriefing and Reflection

Following exploration, the teacher led a whole-class discussion to consolidate understanding. Students explained enzyme functions, compared leading and lagging strand synthesis, and discussed why replication is described as semi-conservative. The simulation was also used to illustrate how replication errors can lead to mutations, prompting students to reflect on the biological significance of accuracy in replication.

4.7.6 Assessing Student Learning

Assessment combined formative and summative approaches. During the lesson, students' responses to simulation quizzes and oral questions provided real-time feedback. At the end, review questions such as "What role does ligase play in replication?" checked comprehension. For homework, students were tasked to (1) draw and label the replication fork, (2) explain the difference between the leading and lagging strands, and (3) outline the sequence of events in DNA replication. These exercises reinforced the learning objectives and provided evidence of individual mastery.

Through this structured process, BiomanBio simulations transformed the abstract process of DNA replication into an interactive, visual, and testable experience, thereby promoting deeper understanding and retention.

5. Results

The participants' data were organised, classified, and coded with the aid of the Statistical Package for the Social Sciences (SPSS) version 26.

The scores from the students in this study were subjected to a normality test to determine whether parametric or non-parametric tests should be used. Normality checks were carried out utilising the numerical approach. Thus, mathematically, the Kolmogorov-Smirnov and Shapiro-Wilk tests were performed. Table 4.1 presents the results of the normality tests.

Table 2: Results of Normality Tests for Students' Scores

	Statistic	Df	Sig.	Statistic	df	Sig.
Pre-test of Control Group	.124	109	.001*	.964	109	.005*
Post-test of Control Group	.110		.002*	.963		.004*
Pre-test of Experimental Group	.205	119	.001*	.897	119	.001*
Post-test of Experimental Group	.140		.001*	.960		.002*

a. Lilliefors Significance Correction
*Significant since $p < 0.05$

Normality checks conducted with the Kolmogorov–Smirnov and Shapiro–Wilk tests (see Table 2) yielded significant values (p = .001, .002, .001, .001 and p = .005, .004, .001, .002, respectively), suggesting that students' performance scores deviated from a normal distribution. Consequently, non-parametric tests, specifically the Mann–Whitney U Test and the Wilcoxon Signed Rank Test, were employed for further analyses.

Research question 1: What is the effect of the computer simulation instructional approach on students' performance in genetics?

A Wilcoxon Signed Rank Test was used to assess changes in students' performance before and after receiving instruction via computer simulation.

Table 3: Wilcoxon Signed Rank Test results on the effect of the computer simulation

Groups	N	Test Statistic	Mean	z	*r*	*P*
Pretest	120	7260.00	8.80	9.52	0.87	0.001*
Posttest			23.30			

*Significant since $p < 0.05$

The test results from Table 4 revealed a statistically significant increase in performance, $z = 9.52$, $p = 0.001$, $r = 0.87$. The mean scores rose from 8.80 on the pre-test to 23.30 on the post-test. The effect size (r = 0.87) indicates a very large and meaningful impact of the computer simulation approach on student achievement in genetics (Fritz *et al.*, 2011).

Research question 2: What are students' perceptions of the computer simulation instructional approach?

This research question sought to determine how students taught using the computer simulation instructional approach perceive its effectiveness. Therefore, to answer this research question, a face-to-face, semi-structured interview was conducted with 15 students. Students' views were recorded with their permission and transcribed for thematic analysis. It was discovered that students had positive perceptions about the integration of the computer simulation instructional approach in teaching genetic concepts. The various themes generated from the interview are presented in Table 4, with explanations and representative statements from students (all names are pseudonyms).

Table 4: Thematic presentation of students' perception on the computer simulation instructional approach

Themes	**Topic**
Theme 1	Better Understanding of Genetic Concepts
Theme 2	Increased Motivation
Theme 3	Retention of the Concept
Theme 4	Engagement and Interactivity
Theme 5	Real-Life Application

5.1 Theme 1: Better Understanding of Genetic Concepts

Students across the participating schools reported that the use of computer simulations significantly enhanced their understanding of genetic concepts, namely, nucleic acids, DNA and RNA structures and functions, DNA replication, and protein synthesis, compared to traditional instructional methods. These topics, often abstract and invisible to the naked eye, were rendered tangible through animated representations and interactive modelling. The simulations allowed students to manipulate genetic structures, observe dynamic processes, and receive real-time feedback, thereby promoting conceptual clarity and improved academic outcomes. These advancements not only facilitated a deeper engagement with the material but also fostered collaborative learning environments where students could explore complex ideas together. As a result, educators observed a marked increase in student confidence and enthusiasm towards the subject matter, ultimately leading to better retention of knowledge.

Rebecca, an SHS 3 student who had struggled with nucleic acids during the pre-test, performed above average in the post-test. She remarked,

> *"Sir, before using the simulation, I didn't understand the difference between DNA and RNA. But in the simulation, I saw their structures, how DNA has two strands and RNA has one. I also saw how uracil replaces thymine in RNA. It all became clear. That's why I was able to answer most of the structure questions correctly in the second test."*

Bernice, a student who had performed at an average level in the pre-test but moved into the high score range in the post-test, added:

"I used to memorise the steps in protein synthesis but never understood how it really happened. The simulation showed how mRNA is formed from DNA and how it moves to the ribosome. Seeing that helped me connect everything. In the test, when I saw questions on transcription and translation, I remembered the animation and answered with confidence."

Amos, a top-performing SHS 3 student, maintained his high performance in the post-test and credited to:

"DNA replication was my hardest topic. I always mixed up the enzymes. But in the simulation, I watched helicase unwind the DNA, and polymerase add nucleotides. It made perfect sense. I could even replay the steps. In the post-test, I didn't guess; I understood what I was writing."

4.2. Theme 2: Increased Motivation

Students expressed that learning genetics through computer simulations reignited their interest in the subject. Previously, many found genetics abstract, unrelatable, or overly difficult. However, the simulations introduced colour, motion, interactivity, and learner autonomy, transforming the classroom from a passive to an engaging learning environment. Students reported looking forward to lessons, willingly exploring additional content, and participating actively behaviours associated with enhanced academic motivation and improved outcomes.

Mavis, a student who initially performed poorly in the pre-test but improved to an average level in the post-test, shared:

"Before, I didn't like biology, especially genetics. I thought it was too hard. But when we started using the simulation, I became excited. Watching how the DNA unwinds and makes copies was interesting. The simulation also helped me to arrange the structure of DNA before proceeding to the next subtopic. I even told my roommate that I finally understood biology. That's why I passed the second test better; I paid attention and really enjoyed the class."

Cindy, an SHS 3 student, also stated:

"I was not someone who asked questions in class. But during the simulation on protein synthesis, I was so curious that I kept raising my hand. I wanted to know more about why the mRNA moves to the ribosome, and how the amino acids join. I studied extra because I wanted to do well in the test, and I did."

Awusah, a naturally curious student who consistently performed at a high level, added:

> *"The simulation made me love genetics. I used to like biology, but now I want to study genetics at the university. Seeing how DNA works, and how proteins are made step-by-step, made me realise how powerful this knowledge is. I prepared for the second test with excitement, and that's why I got almost everything right."*

4.3. Theme 3: Retention of the Concept

Students reported that the simulation-based instruction significantly enhanced their ability to retain and recall genetic concepts. The combination of interactive activities and visual explanations enabled students to internalise processes such as DNA replication, RNA transcription, and protein synthesis. Unlike traditional methods that often relied heavily on text and teacher-centred lectures, the simulation allowed learners to manipulate genetic models, observe step-by-step animations, and revisit difficult processes, thereby strengthening memory through engagement and repetition.

Shadrack, an SHS 3 student, who improved from low to average performance in both tests, noted:

> *"Sir, I usually forget what I study after a few days, especially topics like DNA replication. But after using the simulation, I remembered the roles of helicase, polymerase, and the base-pairing rules even two weeks later. During the test, I could picture how the strands were separating and new ones were forming. That helped me write confidently."*

Nyarko, a student who progressed from average to high performance, reflected on the lesson on RNA and transcription:

> *"Normally, I find it hard to remember scientific terms. But after using the simulation on how mRNA is formed, it just stayed in my mind. I remembered that uracil replaces thymine, and I didn't have to revise it again before the test. That's why I got full marks in that section."*

Cudjoe, a high-performing student, affirmed what Nyarko noticed on how simulations supported his retention of detailed processes:

> *"Protein synthesis was very clear to me after the simulation. I remembered that transcription happens in the nucleus, and translation takes place in the cytoplasm. Even the codons and how they match with anticodons, I didn't forget any of it. I think it's because I saw it in action and not just in diagrams."*

5.4 Theme 4: Engagement and Interactivity

Students who attained high scores in the post-test consistently described the simulation-based lessons as exceptionally interactive and engaging. The instructional approach departed from traditional didactic teaching by enabling learners to actively manipulate genetic processes, such as DNA replication and protein synthesis, in a virtual environment. Through this, students were not merely passive recipients of information but active participants in constructing their own understanding.

Fuseina, a high-performing SHS 3 student, remarked:

> *"Sir, when we were learning about nucleic acids using the simulation, I was completely focused. I explored how the bases paired and tried different sequences to see what would happen. It was very hands-on. The lesson went by so quickly because I was so focused."*

Vivian, who also performed averagely in the pre-test, explained how the simulations enhanced his engagement:

> *"With this method, I wasn't just watching the teacher or reading notes. I was doing the replication process myself, observing the strands unwind and the bases match. It made me feel involved, like I was part of the discovery process. That made it more interesting and helped me retain the steps."*

Crystabel, another high achiever, reflected on the interactive component of the lesson on protein synthesis:

> *"The fact that we could redo the simulation multiple times really helped. I kept practising how the codons matched with the anticodons, and each time I got it right, I felt a sense of progress. It kept me attentive and gave me confidence to answer those questions correctly in the test."*

5.5 Theme 5: Real-Life Application

Students who were in the experimental groups expressed that the simulation-based instruction enabled them to connect complex molecular genetics concepts such as nucleic acids, DNA and RNA structure and functions, DNA replication, and protein synthesis to real-life biological and social contexts. What had previously seemed abstract and difficult to relate to everyday experience was now perceived as tangible and relevant. Through visual representation and interactivity, learners were able to recognise the role genetics plays in personal health, family inheritance, and biological identity.

Quaicoe, an SHS 3 student, shared how the lesson on DNA structure and replication helped him understand the importance of genetics in healthcare:

> *"Before the simulation, I didn't really think genetics had anything to do with real life. But when we learnt about DNA and how it carries information for making proteins, I*

understood how mistakes in DNA can lead to diseases. Now I know why some people are advised to get genetic testing, especially for inherited conditions."

Gifty, an SHS 3 student who scored highly in the post-test, reflected on how the simulation helped her connect genetic information to family traits:

"When we used the simulation to study DNA and RNA, I could clearly see how instructions from DNA are used to make proteins. That helped me understand why certain features run in families. I now know that the way we look, and even some conditions we inherit, are related to how proteins are made in our bodies."

Justice appreciated the connection between protein synthesis and body function, he added that:

"The simulation on protein synthesis helped me see that proteins are not just something we eat, they're made in our bodies based on genetic instructions. I now understand that everything from enzymes to muscle tissue is built from this process. It made biology feel like something happening inside me every day."

6. Discussion

6.1 The Effect of the Computer Simulation Instructional Approach on Students' Performance in Genetics

The Wilcoxon Signed Rank Test revealed a significant improvement in students' performance after being exposed to computer simulations, with an exceptionally large effect size ($z = 9.52$, $p = 0.001$, $r = 0.87$). This marked increase in scores from a mean of 8.80 (pre-test) to 23.30 (post-test) indicates a robust positive impact of the computer simulations on genetics learning.

The cognitive theory of multimedia learning (Mayer, 2009) supports these results by positing that well-designed multimedia tools help learners integrate verbal and visual information more effectively. In genetics, where learners must grasp abstract and dynamic processes, simulations offer experiential learning opportunities that static diagrams or text cannot provide.

Furthermore, research by de Jong and van Joolingen (1998) and Hertel and Millis (2023) showed that simulations foster deeper understanding by encouraging hypothesis testing, prediction, and exploration. Students actively construct knowledge rather than passively receiving information, which aligns with constructivist learning theories (Bada & Olusegun, 2015).

However, critics argue that simulations may not replace the need for hands-on experiments, especially in biology, where tactile engagement with real organisms is crucial (Krüger, 2022). Moreover, the effectiveness of simulations can vary with the quality of the software, teacher training, and students' prior experience with digital tools (Ledger *et al.*, 2022)

Despite these concerns, the strong positive outcomes in this study suggest that simulations, when used appropriately, can serve as effective complements or even alternatives to traditional methods. The exceptionally large effect size reported underscores the importance of integrating digital tools into science curricula to enhance learner outcomes.

6.2 Students' Perceptions of the Computer Simulation Instructional Approach

The findings from the study reveal that computer simulations significantly enhanced students' understanding of complex genetic concepts such as DNA and RNA structures, replication, and protein synthesis. Simulations made abstract content more tangible through animations, interactivity, and real-time feedback, which not only improved conceptual clarity but also increased students' academic confidence and performance. Many students transitioned from memorising steps to genuinely understanding biological processes, a transformation that aligns with Mayer's (2021) cognitive theory of multimedia learning. The interactive and discovery-driven nature of simulations fostered deeper engagement, enabling learners to take an active role in their learning, consistent with Sun *et al.'s* (2022) findings on guidance in simulation-based inquiry learning.

Beyond conceptual understanding, simulations also strengthened student motivation, knowledge retention, and the capacity to link genetic content with real-life applications. Learners expressed renewed interest in biology, with some even indicating aspirations to pursue further studies in genetics. The lessons became more meaningful as students visualised the role of DNA in health, heredity, and protein formation, highlighting the importance of real-world connections in learning. These improvements in engagement and motivation reflect principles of self-determination theory, which emphasises the role of learner autonomy and interest in shaping academic outcomes (Ryan & Deci, 2020). Overall, the use of computer simulations transformed the classroom experience from passive reception to active, student-centred learning.

7. Conclusion

The findings demonstrate that integrating computer simulations into genetics instruction can lead to notable gains in student understanding and academic performance. The approach supports learners in grasping abstract biological processes by making them more visual and interactive. Students' enthusiasm, deeper engagement, and their ability to connect classroom content to real-world phenomena further reinforce the value of simulations in science education. This study concludes that computer simulations are not only an effective instructional alternative but also a transformative strategy that fosters deeper learning, particularly in content-heavy and abstract science topics like genetics.

7.1 Recommendations

1) It is recommended that the Ministry of Education, together with the Ghana Education Service and relevant teacher education institutions such as Colleges of Education and Universities, take responsibility for implementing this initiative. In collaboration with the National Council for Curriculum and Assessment and professional bodies such as the Ghana Association of Science Teachers, these institutions should organise training workshops designed to equip Biology teachers with the requisite skills and pedagogical strategies for effectively integrating simulation-based instructional resources into classroom practice. Such an approach will ensure that teachers are adequately prepared to deliver genetics content through technology-enhanced methods that foster active learning and improved student outcomes.
2) It is also recommended that educational policymakers support the integration of computer simulations into the national science curriculum. This should involve the formulation and implementation of policies that encourage the use of digital tools in science education, particularly in the teaching of genetics. Additionally, measures should be taken to ensure that Senior High Schools are adequately resourced with the necessary infrastructure to facilitate the effective use of simulation-based instructional methods.

Conflict of Interest Statement

The authors declare no conflicts of interest.

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