AKENTEN APPIAH-MENKA UNIVERSITY OF SKILLS TRAINING AND ENTREPRENEURIAL DEVELOPMENT

EVALUATION OF THE EFFECTIVENESS OF COMPUTER SIMULATIONS IN ENHANCING SENIOR HIGH SCHOOL STUDENTS' PERFORMANCE OF GENETICS: A CASE STUDY IN THE NZEMA EAST MUNICIPALITY

RICHMOND MENSAH

2025

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BY

RICHMOND MENSAH

(8237430008)

A thesis submitted to the School of Graduate Studies, Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development in partial fulfillment of the requirements for the award of a Master of Philosophy degree in Science Education

SEPTEMBER, 2025

DECLARATION

Candidate's Declaration

I hereby declare that this thesis, with the exception of quotation and references contained in published works which have been duly acknowledged, is the result of my own original work, and that, no part of it has been presented for another degree in this university or elsewhere.

Richmond Mensah

Signature: ………………………………........... **Date:** …………………………….

Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development.

Rev. Dr. George Oduro-Okyireh (Principal Supervisor)

Signature: ……………………………… Date: ………………………………….

Dr. Daniel Hayford (Co-Supervisor)

Signature: ……………………………… Date: ………………………………….

ACKNOWLEDGEMENTS

I give my highest praise and deepest thanks to the Almighty God, the Creator and Sustainer of the universe, for His unending grace that has brought me this far. May He continue to bless everyone who has contributed to my journey. I am also profoundly grateful to my beloved parents, Nana George Ebissah Kwasi and the late Madam Jemima Kwaw, as well as my dear brothers and sisters, for their constant love and support. My heartfelt thanks also go to Mr. David Afum (Science Teacher, Kwame Nkrumah SHS), Mr. Steven Anaafi (Science HOD, Gwiraman SHS), Mr. Isaac Forjour (Biology teacher, Axim Girls SHS), Mr. Elvis Sarpong (Biology Teacher, Kwame Nkrumah SHS), Mr. Emmanuel B. Agyare (Biology teacher, Kwame Nkrumah SHS) and Mr. Vincent Senoo (HOD, Baidoo Bonsu SHTS) for their invaluable support, guidance, and prayers throughout this academic journey.

I am sincerely indebted to my dedicated and thoughtful supervisors, Rev. Dr. George Oduro-Okyireh, Dean of the Faculty of Education and a Senior Lecturer at the Faculty of Education and General Studies, and Dr. Daniel Hayford, Lecturer at the Department of Integrated Science Education, AAMUSTED, Mampong Campus. Their insightful feedback, patience, and unwavering support played a significant role in shaping this work. I humbly acknowledge that any shortcomings in this work are entirely my responsibility and should not be attributed to them in any way. May the Lord richly bless each one of you for your kindness and support.

DEDICATION

I dedicate this work to my late Mum (Jemima Kwaw), Nana George Ebissah Kwasi, brothers, sisters, nephews, nieces, and all my lovely friends for their prayers and support.

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ABSTRACT

This study evaluated the effectiveness of computer simulations in enhancing Senior High School students' performance of genetics: a case study in the Nzema East Municipality. A quasi-experimental pre-test-post-test non-equivalent group design was used, involving 230 Form Three Biology students from three public Senior High Schools. Data were collected using the Students' Knowledge in Genetics Test (SKGT, pre-test, $\alpha = 0.79$, $\kappa = 0.75$) and the Students' Achievement in Genetics Test (SAGT, post-test, $\alpha = 0.84$, $\kappa = 0.64$), with Cronbach's alpha indicating good reliability for objective items and Cohen's Kappa showing substantial to almost perfect inter-rater agreement for essay items. The Mann-Whitney U test revealed that students taught with computer simulations significantly outperformed those taught conventionally ($U = 2672.00$, $z = -7.82$, $p = 0.001$, $r = -0.52$), demonstrating a large effect size. No significant gender-based differences were found within the simulation group ($p = 0.07$), suggesting equitable benefits across genders. Qualitative findings highlighted enhanced conceptual understanding, motivation, retention, engagement, and real-life connections to genetics. The study recommends integrating computer simulations into the biology curriculum in Nzema East Municipality and across Ghana to improve academic outcomes and deepen conceptual understanding, offering valuable insights for educational practice and policy.

CHAPTER ONE

INTRODUCTION

1.0 Overview

This chapter provides a comprehensive overview of the study, beginning with the context, problem statement, purpose of the study and objectives, as well as its educational significance. The research questions are also presented in detail. Furthermore, the chapter outlines the study's limitations and delimitations, defines essential terms used in the research, and organises the structure of subsequent chapters.

1.1 Background to the Study

Science, as a branch of natural philosophy is essential to the advancement of a country's technological growth. It involves the systematic and structured investigation of the natural world and its phenomena. Science and technology form the foundation of national development and are essential for progress. When effectively utilised, they enhance productivity and address societal needs (Coccia, 2019).

In the 21st century, science education has undergone significant evolution, with a growing emphasis on science, technology, engineering, and mathematics (STEM). This multidisciplinary approach equips students with the knowledge, skills, and experience required in a technologically advanced and rapidly changing world. The integration of digital tools, virtual laboratories, and interactive simulations has become crucial in enhancing student engagement and conceptual understanding (Honey & Hilton, 2018). In addition, efforts to promote equity and accessibility in science education have intensified, ensuring that all students, regardless of their background, receive a quality education. Modern pedagogical strategies prioritise inquiry-based learning and hands-on activities to deepen students' comprehension of scientific concepts (Schmidt et al., 2018).

Science is widely defined as a systematic endeavour that organises knowledge into testable explanations and predictions about the universe. It involves observation, classification, description, experimentation, and theoretical justification of natural phenomena (National Academy of Sciences, 2017). Fundamentally, science is an inquiry driven by curiosity and a desire to understand the natural world. It employs methodologies such as experimentation, hypothesis testing, and data analysis to formulate theories and laws that describe natural processes (Osborne & Dillon, 2016). Additionally, science is empirical, relying on observable and measurable evidence. It follows an iterative process in which hypotheses are continually tested and refined, ensuring that scientific knowledge remains dynamic and evidence-based (DeBoer, 2017).

Learning science is essential for developing critical thinking and problem-solving skills, which are vital in today's rapidly changing world. Science education fosters scientific literacy, enabling students to understand natural phenomena and prepare them for careers in STEM fields. According to Hsu (2018), science education enhances students' abilities to analyse data, conduct experiments, and apply scientific methods, skills valuable both academically and professionally. Furthermore, Stevens et al. (2020) emphasise that effective science education encourages curiosity and innovation, driving societal progress and addressing global challenges such as climate change and public health crises. Incorporating hands-on learning and inquiry-based approaches not only increases students' knowledge but also equips them to contribute to scientific discoveries and make informed decisions (Johnson & Lee, 2021). The influence of science now extends to all areas of human life, including health, agriculture, communication, and engineering.

Biology plays a vital role in science education by providing students with essential knowledge about living organisms and their interactions with the environment. It is crucial for understanding processes from molecular biology to ecosystem dynamics, which are key to solving global challenges such as health, sustainability, and biodiversity conservation (Smith & Johnson, 2019). Including Biology in the school curriculum provides students with the opportunity to participate in hands-on experiments and research, enhancing their critical thinking and problem-solving skills (Brown & Green, 2021). According to Anderson and Li (2022), teaching Biology effectively promotes scientific literacy, enabling students to make informed decisions and contribute to scientific progress. Additionally, inquiry-based learning and real-world applications in Biology prepare students for careers in health, research, and environmental science (Williams, 2020).

However, many scholars have identified ongoing challenges students face in learning biology. For example, Johnson and Lee (2019) found that students in the United States struggle with abstract topics such as genetics and cellular processes due to limited visual and practical experiences. Garcia and Martinez (2021) reported that in Spain, insufficient resources and rigid teaching methods fail to support diverse learning styles. In South Africa, Moyo and Nkosi (2022) emphasised how language barriers and inadequate teacher training restrict students' conceptual understanding. Similarly, Choi and Park (2023) observed that in South Korea, a strict curriculum and an over-reliance on rote memorisation hinder students' engagement with biological concepts, and a comparable challenge has also been reported in Ghana, where science instruction is often dominated by teacher-centred, examination-driven approaches that limit learners' opportunities for inquiry-based exploration (Asano, Amponsah, Baah-Yanney, & Azumah, 2021).

Trends in enrolment at the Senior High School (SHS) level of the educational ladder indicate that biology remains a popular subject among Ghanaian science students. According to Owusu and Aidoo (2017), students often favour biology because they perceive it as connected to health-related careers. The Ghana Education Service (GES, 2020) reports that while biology continues to attract many enrolments, numbers in other science subjects fluctuate due to factors such as teacher availability, resources, and curriculum changes.

Unfortunately, biology students often struggle to balance the demands of the curriculum, especially when practical resources are scarce (Ankomah et al., 2019). Although the Ghanaian government has introduced initiatives such as curriculum reforms and the provision of laboratory equipment, students' performance in biology remains inconsistent (GES, 2020). Asare and Acheampong (2018) attribute this to unequal resource distribution and variations in teacher expertise. Similarly, Akyeampong and Seidu (2021) argue that inadequate teacher preparation and limited opportunities for hands-on learning continue to hinder success in biology education. Adom and Anning (2022) also point out that overcrowded classrooms and the gap between theory and practice diminish the effectiveness of government efforts. Additionally, the Chief Examiners' Reports (WAEC, 2019, 2020, 2021, 2022, 2023, 2024) reveal recurring challenges students face in studying genetics. Many students display limited understanding of chromosome numbers, Mendelian inheritance, and the application of theoretical knowledge in solving genetics problems. Students also often misuse technical terms, resulting in unclear or incorrect answers. These issues underscore the urgent need for improved instructional methods that promote both conceptual understanding and practical application.

International and local studies recommend integrating Information and Communication Technology (ICT), especially computer simulations, to address low science achievement. Chen et al. (2020), Johnson and Smith (2018), and Mensah and Appiah (2022) have shown that ICT tools improve understanding across various science subjects. Simulations are particularly effective in teaching complex processes by offering interactive, visual experiences (Akpan, 2001; Akpan & Andre, 2000; Coleman, 1998).

Although ICT in science education has been studied in Ghana, there is limited research on how computer simulations specifically influence students' knowledge and understanding of genetics. Exploring this gap could provide valuable insights for enhancing performance in biology and science education in general. This study, therefore, aimed to analyse how computer simulations affect students' understanding of genetics. It investigated how these tools can improve conceptual knowledge, boost academic performance, and address ongoing challenges in biology education in Ghana. The results could guide future policies and teaching methods, supporting national efforts to strengthen STEM education (Stevens et al., 2020; Johnson & Lee, 2021).

1.2 Statement of the Problem

In Ghana, the method of instruction in Biology is intended to be activity-based and student-centred, where the instructor acts as a facilitator guiding students to construct knowledge and improve academic achievement (Curriculum Research and Development Division [CRDD], 2012). Since teaching strategies greatly influence learners' success, the Senior High School Biology syllabus emphasises learner-centred and activity-oriented approaches (CRDD, 2012). Unfortunately, the adoption of these recommended methods has not led to improvement in student performance in science, especially biology (Amoah et al., 2018).

Annual reports from the West African Examinations Council (WAEC) consistently indicate that senior high school students struggle to grasp the genetic concepts, especially in molecular biology topics such as nucleic acids, the structure of DNA and RNA, DNA replication, and protein synthesis (WAEC Chief Examiner's Reports, 2019, 2020, 2021, 2022, 2023, 2024). For example, the 2020 WAEC Biology Chief Examiner's Report highlights ongoing difficulties with genetics concepts, particularly in understanding and applying terms such as "diploid" and "polygenic inheritance," which restricted candidates' ability to address related questions effectively. Many candidates failed to correctly define "diploid" as the state of possessing two complete sets of chromosomes (2n) in somatic cells or to explain "polygenic inheritance" as traits governed by multiple genes, resulting in continuous variation (e.g., skin colour or height). This led to inaccuracies, such as confusing polygenic traits with simple Mendelian inheritance patterns or misrepresenting chromosome behaviour during meiosis. The 2019 report revealed continued difficulty in defining terms such as "diploid" and "polygenic inheritance," limiting their ability to answer related questions effectively. The 2021 report highlighted challenges in understanding the function of ribonucleic acid (RNA) in protein synthesis, distinguishing it from deoxyribonucleic acid (DNA), and explaining DNA replication, attributed to ineffective teaching strategies that lacked adequate molecular visualisation and practical application.

In 2023, students performed poorly in genetics, with notable challenges in drawing and interpreting Punnett squares for dihybrid crosses. A considerable number struggled with the correct use and spelling of genetic terminology, while their diagrams of genetic processes were often inaccurate. Frequent errors were also observed in differentiating between genotype and phenotype as well as in describing sex-linked inheritance, which caused many to lose marks. The 2024 report further showed struggles in transcribing messenger RNA (mRNA) sequences from DNA, drawing genetic crosses, and interpreting inheritance patterns, revealing weaknesses in understanding the central dogma of molecular biology, which involves DNA replication and protein synthesis. Many students avoided genetics questions or answered them imprecisely, indicating inadequate understanding of the concept and instructional deficiencies.

Persistent poor performance in molecular genetics topics such as nucleic acids, DNA and RNA structure, DNA replication, and protein synthesis significantly impacts students' overall performance in biology, prompting stakeholders to seek effective solutions. Researchers have pointed out several factors that make learning molecular genetics difficult for students. These include the highly abstract nature of genetic concepts (Ekong et al., 2015; Rotbain et al., 2008), learner-related issues such as prior knowledge and motivation (Thomson, 2018; Westwood, 2017), limited access to appropriate teaching and learning resources (Adewale et al., 2016; Chifwa, 2015), as well as the instructional strategies employed by teachers (Appiah, 2012; Kılıç et al., 2016).

Given the influence of teaching methods on performance, the Senior High School Elective Biology curriculum recommends constructivist approaches to improve learning outcomes. However, while the syllabus advocates constructivism, it does not specify strategies for teaching molecular genetics. Therefore, it is essential to explore the effectiveness of constructivist strategies in teaching key biology concepts. Computer simulations, known for their interactive and visual qualities, have been proven effective in teaching complex science topics by helping students visualise abstract ideas and increasing engagement (Akpan & Andre, 2000; Marbach-Ad et al., 2008).

Although there is evidence supporting the advantages of computer simulations, limited research has examined their application and impact within the Ghanaian educational setting. Therefore, investigating the effect of computer simulation-based instruction on teaching and learning complex, challenging biology concepts, such as genetics in Ghanaian Senior High Schools, is both timely and essential.

1.3 Purpose of the Study

This study evaluated the effectiveness of computer simulations in enhancing Senior High School students' performance of genetics : a case study in the Nzema East Municipality.

1.4 Objectives of the Study

The study is guided by the following objectives:

1. To determine the difference in academic performance between students taught genetics with computer simulation instructional strategies and those taught with traditional methods.
2. To examine whether there is a significant difference in the academic achievement of male and female students when taught with computer simulation-based instruction.
3. To evaluate the impact of computer simulation-based instructional strategies on students' achievement in genetics.
4. To find out how students perceive the computer simulation-based instruction in genetics.

1.5 Research Questions

1. What is the academic performance between students taught genetics with computer simulation-based instruction and those taught with traditional methods?

2. What is the difference in academic performance between male and female students taught using computer simulation-based instruction?
3. What is the effect of computer simulation-based instruction on students' performance in genetics?
4. What are students' perceptions of the computer simulation-based instruction in genetics?

1.6 Significance of the Study

The present study investigated how the use of computer simulations as a teaching strategy influences the academic achievement of Senior High School (SHS) students in genetics with the Nzema East Municipality, specifically focusing on Kwame Nkrumah Senior High School, Gwiraman Senior High School and Axim Girls Senior High School. According to Hogarth et al. (2006), computer simulations have proven effective in communicating scientific concepts and processes, making them a valuable tool in science education. This study aimed to produce a comprehensive report on the effect of integrating computer simulations into the teaching and learning of biology on students' understanding and performance in genetics in the selected Senior High Schools with Nzema East Municipality. It aspired to transform biology education by moving away from traditional methods such as lectures, discussions, and demonstrations towards incorporating computer simulations into classroom lessons in Kwame Nkrumah Senior High School, Gwiraman Senior High School and Axim Girls Senior High School.

The integration of these simulations was expected to deliver notable academic benefits by enhancing learners' creativity, critical thinking, problem-solving, communication, and analytical skills (Trucano, 2005). By highlighting these benefits, the study aimed to encourage a more engaging and effective approach to biology instruction, providing students with a platform to excel both academically and intellectually in the context of Nzema East Municipality.

Additionally, the study aimed to guide school administrators in prioritising investments in relevant ICT tools and educational software to improve the teaching and learning of biology in Kwame Nkrumah Senior High School, Gwiraman Senior High School and Axim Girls Senior High School. The provision of these resources was designed to support schools in modernising their instructional methods and enhancing the overall learning environment for biology students across the Nzema East Municipality. Moreover, the findings of this research were expected to serve as a valuable resource for the Ministry of Education (MoE), the Ghana Education Service (GES), the Curriculum Research and Development Division (CRDD), and other key stakeholders in the field of science education. The study aimed to provide a strong foundation for advocating the inclusion of computer simulations into the national biology curriculum. It also aimed to offer an evidence-based justification for increased budget allocations towards acquiring ICT tools and developing digital learning resources to strengthen science education in Ghana. Finally, the research was expected to contribute to academic discourse on innovative teaching strategies by serving as a point of reference for future studies. It would provide insights for researchers interested in exploring the effectiveness of computer simulations in enhancing the teaching and learning of genetics and other components of biology within Nzema East Municipality and its Senior High Schools.

1.7 Limitations of the Study

As explained in the methodological literature, limitations refer to factors often beyond the researcher's control that may influence the outcomes or interpretation of a study (Creswell & Creswell, 2018). In the present research, several such limitations were acknowledged. Firstly, it was not possible to control for extraneous factors such as students' age, maturity, prior knowledge, and ability levels. These variables, which are physiological and contextual in nature, may have contributed to variations in learning outcomes. To mitigate this challenge, intact classes offering Biology were selected, which helped reduce but not eliminate potential biases.

Secondly, despite efforts to ensure internal validity through careful sampling, piloting of research instruments, and fidelity to the experimental procedures, external factors such as classroom dynamics, peer influence, and teacher–student interactions may still have influenced the results. As educational researchers have observed, classroom-based interventions are subject to natural variability that cannot be fully controlled (Cohen et al., 2018).

Finally, the study was geographically restricted to Senior High Schools within the Nzema East Municipality. This limitation reduces the extent to which the findings can be generalised to schools in other regions with different socio-economic or infrastructural contexts. Furthermore, the research was conducted within the span of a single academic term, which limited the ability to assess the long-term sustainability of learning gains. As such, while the findings offer useful insights, caution is advised when applying them to broader contexts.

1.8 Delimitation of the Study

This study specifically examined the use of computer simulation-based instruction in teaching genetics concepts to senior high school students. It took place in three schools: Kwame Nkrumah Senior High School in Nsein, Axim Girls' Senior High School in Axim, and Gwiraman Senior High School in Bamianko, all situated within the Nzema East Municipality of the Western Region, Ghana. The participants were exclusively SHS 3 students enrolled in Science or Home Economics programmes, who were taking Biology as an elective subject at the selected schools. Additionally, the study focused on the genetic content outlined in the elective Biology curriculum for SHS students (Section Three, Unit Four, pp. 74–78).

1.9 Definition of Terms

Academic achievement: The pre-test and post-test scores from before and after the course will be used to assess the academic achievement of the participants in this study.

Genetics: In this sense, genetics refers to RNA transcription, deoxyribonucleic acid replication, and the structures and activities of nucleic acids**.**

Perception: A person's view, belief, or thought that is founded only on outward appearances is referred to as their perception**.**

Sex: The state of being male or female

STEM: science, technology, engineering and mathematics

Computer: computer is an electronic device that can receive data (input), process it according to a set of instructions (called a program), store it, and produce results (output). It can perform a wide range of tasks quickly and accurately, including calculations, data analysis, communication, and control of other devices

Computer simulations: Computer simulations are interactive digital models that replicate real-world processes or systems, allowing users to experiment, visualise, and manipulate variables to observe outcomes. They serve as powerful educational tools, particularly in science education, where they can help learners grasp complex concepts that are difficult to understand through traditional teaching methods.

1.10 Organisation of the Study

This study is organised into five comprehensive chapters, each serving a specific purpose in addressing the research problem and objectives. The first chapter introduces the study by providing a detailed background that situates the research within the broader educational landscape of Ghana. It clearly articulates the problem statement, outlining the rationale for the investigation and identifying the gap in existing knowledge. This chapter further outlines the objectives guiding the study and the research questions it aims to answer. Additionally, it discusses the significance of the research, highlighting its potential contribution to educational practice and policy. It also establishes the delimitations and limitations that define the scope and boundaries of the study, providing operational definitions for key terms and concepts to ensure clarity and consistency throughout the report.

Chapter Two presents a comprehensive review of relevant literature, synthesising theoretical perspectives and empirical studies related to molecular genetics instruction. It discusses foundational theories underpinning the study, including constructivist approaches to teaching and learning, and establishes a conceptual framework that guides the investigation. This chapter also critically examines previous research findings, identifying patterns, contradictions, and gaps that further justify the need for the current study.

Chapter Three details the method used in the current study. It explains the research design adopted, the population from which the sample was drawn, and the sampling techniques used to ensure representation and reliability. It also describes the instruments used for data collection, the procedures followed in gathering the data, and the ethical considerations observed throughout. It concludes with a discussion on how the data were analysed to help draw valid, reliable conclusions.

Chapter Four is dedicated to presenting, analysing, and interpreting the findings. It shows the data in a clear and organised manner, using tables and figures where necessary. It also discusses the results in relation to the research questions and the relevant literature. To conclude, the chapter discusses the implications of the findings, highlighting similarities and divergences with previous studies, and reflecting on their significance for teaching and learning molecular genetics.

Finally, Chapter Five provides a concise summary of the study, reiterates the main findings, and draws conclusions based on the evidence gathered. It discusses the implications for educational practice, particularly within the context of science education in Ghana, and offers recommendations for policy, teaching practice, and future research. This chapter aims to consolidate the study's contributions and suggest directions for ongoing improvement and scholarly development inquiry.

CHAPTER TWO

LITERATURE REVIEW

2.0 Overview

This chapter provides a comprehensive review of the literature related to the effectiveness of computer simulations in teaching genetics. It starts by examining the theoretical framework, highlighting Constructivism as developed by Piaget and Vygotsky, and its impact on simulation-based learning. This section demonstrates how constructivist principles underpin interactive and student-centred approaches in genetics education. Following this, the conceptual framework presents a structured model showing the relationships among instructional strategies, student engagement, and learning outcomes in genetics. The discussion then shifts to computer simulations in science education, highlighting their importance, benefits, and applications in supporting conceptual understanding. A more detailed analysis is provided on computer simulations in genetics education, focusing on their role in helping students grasp abstract concepts in genetics. Furthermore, the chapter examines challenges in teaching and learning genetics, emphasising difficulties students face and the limitations of traditional instructional methods. A review of empirical studies on the effectiveness of computer simulations follows, comparing simulation-based learning with conventional approaches in science education. Finally, the research gaps and justification for the study are discussed, identifying areas needing further investigation and emphasising the importance of this research in improving the teaching of genetics.

2.1 Theoretical Framework of the Study

Different perspectives exist on how individuals acquire knowledge, leading to the development of various learning theories. Educators apply diverse instructional methods based on these theories in their classrooms. Some of the core learning theories include behaviourism, cognitivism, and constructivism. This study is grounded in the constructivist framework, which aligns with its focus on students' cognitive engagement and academic development. Several well-known scholars have made significant contributions to the constructivist paradigm, including John Dewey, Jean Piaget, Lev Vygotsky, and Jerome Bruner. Constructivism examines the nature of human knowledge, particularly within scientific learning, and the processes through which learning takes place and knowledge is validated. Essentially, constructivism asserts that individuals actively construct their understanding of the world based on personal experiences and reflective thought (Bhattacharjee, 2015).

Constructivist principles suggest that students acquire knowledge through meaningful experiences, either independently or collaboratively, engaging in interactive learning activities (Koehler et al., 2021). According to Khan et al. (2022), constructivist teaching requires educators to foster an engaging and supportive learning environment, considering students' backgrounds, previous experiences, and personalised learning objectives. Therefore, the teacher's role is to serve as a facilitator, while students take an active part in directing their own learning (Burroughs, 2023).

Honebein et al. (1993) argue that constructivist learning environments should incorporate context and authentic activities to enhance understanding. Constructivism is also central to applying the Generative Learning Strategy, which promotes the acquisition of meaningful knowledge. This theoretical perspective underscores the importance of prior knowledge and active involvement in shaping new learning experiences. As Arhin (2023) notes, constructivist approaches improve students' learning outcomes by integrating their pre-existing beliefs and cognitive frameworks into teaching strategies.

Furthermore, constructivist theory helps explain how prior knowledge affects learning results and instructional effectiveness. It can be categorized into three primary forms: cognitive constructivism, social constructivism, and radical constructivism (Doolittle & Hicks, 2003).

Although all emphasise knowledge construction, they differ in focus. Cognitive constructivism, based on Piagetian principles, suggests that individuals actively build knowledge by relating new experiences to prior understanding (Roschelle, 1997). Conversely, radical constructivism argues that knowledge is created subjectively rather than being acquired objectively, highlighting the role of interpretation in learning (Bettencourt, 2012). Meanwhile, social constructivism, rooted in Vygotsky's work, stresses the importance of social interactions in the learning process. Mishra (2023) states that social constructivism asserts that learners develop knowledge through collaborative engagement within a social setting.

Vygotsky's concept of the Zone of Proximal Development (ZPD) is vital to social constructivist theory. It describes the gap between what a learner can do independently and what they can achieve with guidance from a knowledgeable peer or teacher (Vygotsky, 1978, as cited by Lee, 2024). The ZPD highlights the importance of scaffolding, where learners receive temporary support to close understanding gaps. According to Shabani (2020), social interaction within the ZPD improves comprehension, as students clarify their understanding through dialogue and cooperation. This aligns with cooperative learning methods, where peer discussions contribute to the construction of knowledge.

The implications of constructivism for teaching are significant. Melero et al. (2012) argue that effective constructivist teaching involves scaffolding learning, promoting peer collaboration, and presenting new concepts at an appropriate level of challenge. If a task is too simple, learners may lose interest; if it is too hard, they may become frustrated. Maintaining an optimal challenge level helps maximise student engagement and understanding (Davis et al., 2012).

Social constructivism relies on key assumptions about reality, knowledge, and learning (Kim, 2001). It claims that reality is socially constructed, knowledge emerges from cultural interactions, and learning is a social activity rather than just an individual cognitive process. Amineh and Asl (2015) emphasise that language is a key tool in shaping reality, as individuals develop understanding through social interactions.

Therefore, knowledge is not simply acquired; it is co-constructed within a cultural and social context (Kim, 2001).

Teachers play a crucial role in fostering a constructivist learning environment by prioritising student inquiry over passive knowledge transfer. Machumu and Zhu (2017) suggest that constructivist educators encourage active student participation, promote meaningful activities, and assess learning through shared understanding rather than rigid testing. Cooperative learning is a key aspect of constructivist teaching, where students participate in discussions, challenge each other's perspectives, and collaboratively improve their understanding (Renninger, 2024). Husain (2023) states that students in constructivist classrooms actively explore new concepts, refining their knowledge through inquiry-based methods.

Schmidt et al. (2024) suggest that designing learning experiences can be guided by constructivist ideas, particularly the focus on processes through which individuals make meaning out of lesson delivery activities. This view challenges traditional notions of knowledge as fixed and objective, instead suggesting that individuals interpret experiences based on prior understanding. Hence, learning becomes a process of meaning-making rather than passive absorption of information.

Constructivist environments promote experiential learning, encouraging students to explore concepts through real-world applications (Bada, 2015). Using diverse teaching methods, such as multimedia, case studies, and interactive discussions, enhances engagement and supports knowledge building (Honebein, 1996).

Moreover, constructivist learning settings should challenge students without overwhelming them. Caine and Caine's (1994) principles emphasise that effective learning occurs in intellectually stimulating yet non-threatening environments. This aligns with Vygotsky's Zone of Proximal Development and the concept of scaffolding, where students receive temporary support that gradually diminishes as they develop independence (Wood et al., 1976).

Ultimately, constructivism asserts that context, values, and individual cognitive frameworks influence learning. Different learners may derive different meanings from the same instructional content, depending on their prior knowledge and experiences. Therefore, teachers need to consider students' existing understanding when planning teaching strategies. Constructivist educators should create environments that foster active participation, inquiry, and critical thinking. Posner et al. (1982) emphasise that effective constructivist teaching involves addressing students' misconceptions and guiding them towards scientifically accepted concepts through interactive dialogue.

In conclusion, constructivism provides a strong theoretical basis for student-centred learning, focusing on active participation, collaboration, and critical questioning. Teachers act as facilitators, guiding students in the process of meaning-making while recognising the importance of prior knowledge and social interaction. As the constructivist approach continues to influence educational research, its core principles remain vital for nurturing deep and meaningful learning experiences.

Using constructivism as the guiding theory, computer simulation–based instruction is highly suitable because it enables students to learn through active engagement rather than simply receiving information. Constructivist scholars such as Piaget argue that learners develop understanding by interacting with their environment, whilst Vygotsky stresses the importance of guided support to help students make sense of new concepts. Computer simulations reflect these principles by giving learners opportunities to explore genetic processes, test ideas, and receive immediate feedback in ways that traditional classroom teaching often cannot offer. This is particularly important in contexts like Ghana, where science lessons commonly rely on teacher-centred, examination-driven approaches that provide limited opportunities for inquiry and hands-on learning. By allowing students to visualise and experiment with complex genetics concepts in an interactive environment, simulations promote deeper and more meaningful understanding, making this approach a theoretically sound and effective method for enhancing learning in genetics.

2.2 Conceptual Framework of the Study

A conceptual framework is a structured representation of the main variables and their presumed relationships within a study (Fig. 2.1). It acts as a roadmap linking the theoretical foundations of a research topic to its empirical investigation, guiding the researcher in designing, collecting, and interpreting data (Adom et al., 2018). According to Miles et al. (2014), a conceptual framework clarifies the constructs under study and provides a visual or narrative form illustrating how variables are interconnected based on existing theories and prior research. Essentially, it offers clarity and coherence, enabling the researcher to identify the dependent, independent, mediating, and moderating variables in a way that explains how outcomes are expected to unfold.

In this study, a conceptual framework has been developed to evaluate the efficacy of instruction grounded in computer simulation strategy in enhancing the academic performance of Senior High School students in genetics. The framework identifies the computer simulation strategy as the independent variable, which is expected to influence students' academic performance in genetics, the dependent variable, either directly or indirectly. Positioned between these two is students' perception, which acts as a mediating variable. This suggests that the effect of the simulation strategy on academic achievement may operate through students' interpretation, engagement, and receptivity to the strategy. When students find the simulation engaging, accessible, and helpful for visualising abstract concepts, their learning outcomes are likely to improve.

Furthermore, gender functions as a moderating variable. This implies that the relationship between the computer simulation strategy and students' academic performance might differ depending on whether the student is male or female. Previous studies have shown that gender differences can influence how learners interact with digital tools and simulations (Ting, 2020). Consequently, understanding these moderating effects provides greater insight into the fairness and inclusivity of the instructional approach. Overall, the framework provides a comprehensive structure for examining not only the direct impact of simulation on learning outcomes but also the psychological (perception) and demographic (gender) factors that could influence the intervention's effectiveness.

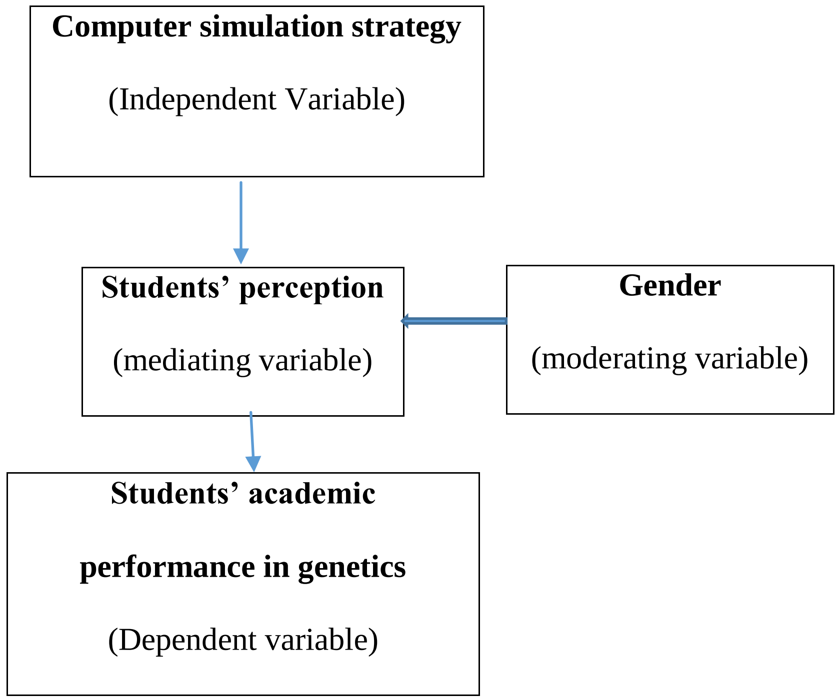

Figure 2.1: Conceptual framework of the study

2.3 Overview of Genetics in the SHS Curriculum with Emphasis on DNA, RNA, and Protein Synthesis

The teaching of genetics in the Senior High School (SHS) Elective Biology curriculum, as outlined in the 2010 syllabus by the Ghana Education Service, is designed to introduce learners to the principles of heredity, variation, and molecular biology. Genetics is taught within the broader theme of heredity and includes key units such as inheritance, Mendelian genetics, chromosomal behaviour, and modern molecular genetics. Of particular interest in this study are the subtopics on DNA and RNA structures, DNA replication, and protein synthesis, which form the molecular basis of inheritance and gene expression.

The curriculum begins with the concept of heredity and the transmission of traits via genes located on chromosomes. Students are introduced to classical genetics through Mendel's laws, monohybrid and dihybrid crosses, sex determination, and examples of inherited conditions such as albinism and sickle cell anaemia. This foundation prepares students for more complex molecular concepts.

A key focus of the curriculum is molecular genetics, which introduces students to deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) as the chemical substances responsible for carrying and transmitting genetic information. DNA stores the hereditary instructions that determine an organism’s traits, whilst RNA helps convert these instructions into proteins and supports various cellular processes essential for life.

Learners are expected to identify and describe the molecular structures of DNA and RNA, including components such as phosphate groups, pentose sugars, and nitrogenous bases, and to distinguish between the structural features of the two molecules. The double helix model of DNA is emphasised as fundamental to its role in accurate replication and information storage. Students are further guided through DNA replication, where they learn how the double-stranded DNA unwinds and synthesises two identical copies before cell division. DNA replication ensures each daughter cell receives an exact copy of the genetic material, highlighting the role of DNA in maintaining genetic continuity.

Another critical area of focus is protein synthesis, which is taught in two main stages: transcription and translation. During transcription, students learn how a complementary mRNA strand is formed from the DNA template. In translation, this mRNA is decoded at the ribosome to assemble a specific sequence of amino acids, resulting in the formation of a functional protein. The curriculum encourages students to relate these processes to the expression of traits and functioning of cells.

Additionally, the syllabus covers variation and genetic engineering, enabling students to explore genetic diversity, sources of variation (such as crossing over and mutation), and modern biotechnological applications, including recombinant DNA technology, cloning, and ethical considerations in genetics.

To facilitate understanding, the curriculum promotes practical activities such as drawing diagrams of DNA and RNA, constructing models of nucleic acids, solving genetic cross problems, and participating in classroom discussions on genetic disorders and biotechnology. These interactive methods aim to demystify abstract concepts and foster critical thinking.

In summary, the genetic component of the SHS biology curriculum provides learners with a comprehensive understanding of how traits are inherited and expressed at both classical and molecular levels. Emphasising DNA and RNA structures, DNA replication, and protein synthesis equips students with essential knowledge foundational for careers in medicine, agriculture, biotechnology, and other science-related fields. It also empowers students to make informed decisions on bioethical issues in an increasingly genetically driven world.

2.4 Computer Simulations in Science Education

Computer simulations refer to digital models designed to replicate real-world processes or systems in a virtual environment, allowing users to manipulate variables and observe outcomes over time. In science education, particularly biology, computer simulations are used as instructional tools that enable learners to visualise and interact with phenomena that are otherwise abstract, complex, or difficult to observe directly (de Jong & van Joolingen, 1998). These simulations create dynamic learning environments where students can experiment, explore relationships, and test hypotheses without the constraints of a physical laboratory.

Rooted in constructivist learning theories, which emphasise active learner engagement and knowledge construction through experience (Rutten et al., 2012), simulations integrate visual, textual, and sometimes auditory elements to cater to multiple learning styles, enhance conceptual understanding, and promote retention. They are especially effective in subjects such as genetics, where students need to grasp invisible and abstract processes like DNA replication, protein synthesis, and inheritance patterns. Several types of computer simulations are commonly employed in science education:

1. Interactive Simulations: These enable users to manipulate variables and receive immediate feedback. For example, a genetics simulation might allow students to perform virtual crosses between organisms and observe resulting genotypes and phenotypes. Such simulations foster inquiry-based learning and critical thinking (Smetana & Bell, 2012).

2. Model-Based Simulations: These incorporate scientific models within the simulation to represent biological or physical systems. They emphasise the relationship between theoretical knowledge and observed outcomes. Often involving iterative experimentation, these simulations help students understand causality and complex interactions (de Jong & van Joolingen, 1998).
3. Game-Based Simulations: These integrate game mechanics such as scoring, levels, or challenges to make learning more engaging. While maintaining educational value, they aim to improve motivation and attention, especially for students who may find traditional instructional approaches less appealing (Cheng & Annetta, 2012).
4. Micro-worlds: These are simplified, self-contained environments designed to model specific scientific principles or scenarios. A micro-world in genetics, for example, might simulate a virtual cell whereby students manipulate DNA strands and observe transcription and translation processes. Micro-worlds provide learners with a focused context for exploration without the distractions of broader system complexity (Papert, 1980).

The effectiveness of each type of simulation largely depends on the instructional design, learning objectives, and the level of interactivity it offers. Proper scaffolding and teacher support are crucial to ensure students gain meaningful insights from simulation activities. Without guidance, learners may engage superficially, missing the conceptual depth that the simulation aims to provide (Rutten et al., 2012).

Computer simulations are widely recognised for their capacity to enhance students' conceptual understanding, particularly in complex subjects like genetics, where abstract processes and microscopic phenomena are central. Simulations allow students to engage directly with processes that are difficult to observe in the natural world, such as DNA replication, genetic inheritance, and protein synthesis. By providing visual and interactive representations, they bridge the gap between theoretical knowledge and real-world application, aiding comprehension of these abstract concepts (Rutten et al. (2012). One key strength of simulations in education is their ability to provide interactive learning experiences. As de Jong and van Joolingen (1998) note, simulations enable students to manipulate variables and observe the consequences in real time. A genetics simulation, for example, might allow experimentation with different crosses and the observation of resulting phenotypes, reinforcing understanding of Mendelian inheritance and probabilistic outcomes. This hands-on approach encourages the exploration of cause-and-effect relationships, hypothesis testing, and prediction, which are essential to the scientific learning method.

Additionally, technological limitations may restrict the widespread use of simulations, especially in resource-constrained educational settings. Many schools, particularly in developing countries, may lack the necessary infrastructure, such as high-speed internet or access to computers, to fully implement simulation-based learning. These logistical challenges could hinder the effective use of simulations in science education (Asimeng-Boahene, 2020).

Despite these challenges, the role of simulations in improving conceptual understanding in genetics education remains invaluable. When implemented thoughtfully and with adequate support, simulations promote deeper engagement, critical thinking, and retention. As technology continues to develop, simulations are becoming increasingly immersive and interactive, further transforming the way complex biological concepts are taught and comprehended.

There are many advantages to using computer simulations in education. This is especially true in teaching complex subjects such as genetics. One of the main benefits is their ability to give students a clear visualisation of abstract or microscopic processes that are often hard to observe in a traditional classroom setting. In genetics, processes such as meiosis, genetic recombination, and DNA transcription can be difficult to understand without visual aids (Smetana & Bell, 2012). Simulations enable students to observe genetic material in action. This enhances their understanding of the molecular mechanisms involved, improving their conceptual understanding. Additionally, these digital tools allow students to interact with dynamic systems in ways that traditional textbooks cannot, leading to improved learning outcomes (Knezek & Christensen, 2016).

Simulations promote active learning because they provide students with the opportunity to engage directly with the material. According to de Jong and van Joolingen (1998), simulations provide students with interactive experiences as they manipulate variables, conduct experiments, and observe real-time results. This hands-on approach encourages deeper engagement and fosters critical thinking, as students become actively involved in the learning process rather than passively receiving information. The interactive nature of simulations also supports problem-solving and inquiry-based learning, helping students develop higher-order thinking skills (Rutten et al., 2012). Furthermore, simulations provide students with opportunities to make mistakes in a low-stakes environment, thereby encouraging self-directed learning and reflection (Boulter & Buckley, 2000).

Another advantage of simulations is the immediate feedback they provide. As students interact with the simulation, they receive instant feedback on their actions, allowing them to recognise and correct errors in real time. This feedback loop encourages self-regulated learning, enabling students to adjust their strategies and thinking depending on responses (Cheng & Annetta, 2012). The capacity for self-correction further strengthens learning and deepens understanding. Simulations also offer the opportunity for repeated practice, which is essential for mastering complex concepts. For example, students can perform multiple trials in a genetic crossing simulation to explore different genetic outcomes, helping to develop a clearer understanding of inheritance patterns and probability. This repetition allows for gradual mastery over time (Smetana & Bell, 2012). Additionally, because simulations can often be repeated multiple times without resource constraints, they help bridge the gap between theory and practice (Barab et al., 2007).

Furthermore, simulations allow diverse learning styles. They include various modes of interaction, which help accommodate visual, auditory, and kinesthetic learners. Visual learners benefit from graphical representations and animations, auditory learners engage with narrations, and kinesthetic learners manipulate variables and observe changes within the simulation. This multimodal approach ensures that a wide range of students can engage with the material in ways that suit their learning preferences (Cheng & Annetta, 2012). This inclusivity promotes more equitable learning experiences for diverse students (Liu et al., 2011).

However, despite their numerous benefits, simulations have limitations. One major challenge is the technological barriers faced by schools. Many schools, especially those in resource-limited settings, may lack the necessary infrastructure, such as computers, high-speed internet, or specialised software, to effectively implement simulations in the classroom. This scarcity of technological resources can create disparities in learning opportunities, particularly in developing countries (Asimeng-Boahene, 2020). Without the right tools and access to technology, the full potential of simulations cannot be realised (Parker & Heywood, 2000).

Moreover, simulations require proper teacher facilitation to be most effective. While they are interactive, students may struggle to benefit fully without guidance. Educators need to ensure that students focus on the scientific concepts and reflect on their actions within the simulation; otherwise, students may become distracted or overly focused on the technology itself. To maximise the educational value of simulations, teachers should actively guide the learning process, helping students connect their experiences in the simulation to the broader curriculum (Rutten et al., 2012). Furthermore, if simulations are used without a clear instructional framework, they may not lead to deep learning or conceptual understanding (Knezek & Christensen, 2016).

Another limitation of simulations is the often-limited real-world context included. While simulations effectively visualise abstract concepts, they frequently do not capture the full biological complexity and environmental factors that influence genetic expression in living organisms. For instance, a simulation of protein synthesis may not fully reflect the intricate regulatory mechanisms involved in gene expression within biological systems. Therefore, it is vital to use simulations together with other instructional strategies that incorporate real-world examples and hands-on activities (Smetana & Bell, 2012). Some researchers also argue that simulations can oversimplify the complexity of real-life phenomena, risking misconceptions if students are not carefully guided through the learning process (Boulter & Buckley, 2000).

Simulations tend to oversimplify complex biological systems to make them more accessible to students. While this simplification is helpful for teaching, it can sometimes cause misconceptions if students are unaware of the true complexities of biological processes. For example, a simulation that demonstrates genetic inheritance may not account for all the variables influencing gene expression, potentially leading students to misunderstand how genes interact in real organisms. Educators must ensure students grasp the limitations of these models and promote further exploration beyond the simulation (Cheng & Annetta, 2012).

Finally, simulations can cause cognitive overload if not designed carefully. When they contain too many variables or present information too quickly, students may become overwhelmed and struggle to focus on the key concepts. To prevent cognitive overload, simulations should be well-structured, allowing for gradual processing of information, so students can absorb the material without feeling overwhelmed (de Jong & van Joolingen, 1998).

Although simulations offer several benefits for understanding complex topics such as genetics, they also have limitations that need to be considered. Their effectiveness largely depends on how well they are integrated into the curriculum, the availability of technological resources, and the role of teachers in guiding learning. When used appropriately, simulations can significantly enrich the educational experience by providing interactive, engaging, and personalised learning opportunities.

2.5 Instructional Strategies in Genetics Education

Instructional strategies in genetics education have developed in response to the complex nature of the subject. Genetics requires students to understand abstract and often invisible processes, such as DNA replication and inheritance patterns, which necessitate more than superficial learning techniques (Lewis et al., 2000). Consequently, science educators have increasingly adopted instructional approaches that extend beyond traditional methods. Strategies such as inquiry-based learning, cooperative group activities, problem-solving tasks, and technology-enhanced instruction are now valued for their ability to deepen conceptual understanding and boost student engagement (de Jong & van Joolingen, 1998). These approaches align with constructivist theories of learning, which emphasise active participation and knowledge construction rather than passive reception.

Moreover, the use of technology enhances personalised learning. Students can progress at their own pace, revisit difficult content, and engage with simulations according to their learning styles. Studies have shown that technology-supported inquiry improves student performance, motivation, and retention, especially when aligned with well-structured instructional scaffolds (Hmelo-Silver et al., 2007; Makransky et al., 2019). These technologies also offer opportunities for differentiated instruction, enabling teachers to support diverse learners more effectively.

Despite these benefits, the successful implementation of inquiry-based and technology-enhanced approaches depends on several contextual factors. In resource-limited settings like many Ghanaian SHSs, challenges due to a lack of infrastructure, including insufficient computers, unreliable electricity, and inadequate internet connectivity, can hinder the integration of digital tools into science instruction (Ghana Education Service, 2019). Additionally, teacher preparedness and training in the use of inquiry methods and educational technologies play a critical role. Many science educators require ongoing professional development to confidently integrate simulations and inquiry strategies into their lessons (Yidana, 2020).

To address these barriers, education policymakers and curriculum developers have advocated for the incorporation of ICT into science education through initiatives like the ICT in Education Policy and the Science, Technology, Engineering, and Mathematics (STEM) enhancement programs. These efforts aim to build teacher capacity, improve access to educational technology, and foster innovative teaching practices that enhance scientific literacy and 21st-century competencies among students. Inquiry-based and technology-enhanced strategies offer a powerful pedagogical framework for improving genetics education. As they foster active participation and provide tools that make invisible processes visible, these approaches help learners construct meaningful scientific knowledge and prepare them for future studies in biology and related fields.

The effectiveness of computer simulations as an instructional method in science education, particularly in teaching abstract concepts like genetics, has been widely compared to traditional teaching methods. Traditional instruction, often characterised by teacher-led lectures, textbook-based learning, and rote memorisation, has been the mainstay in many classrooms, especially in resource-limited settings. While this method is efficient for content delivery and syllabus coverage, it often lacks the interactive elements necessary for deep conceptual understanding and critical thinking (Adu-Gyamfi et al., 2016; Opoku-Asare, 2014).

In contrast, computer simulations offer a dynamic, interactive, and student-centred learning experience. They enable learners to visualise and manipulate complex biological processes such as DNA replication, meiosis, and protein synthesis, which are difficult to observe in real-time using traditional methods (Rutten et al., 2012). By providing visual and experiential representations of genetic phenomena, simulations enhance understanding, particularly for students who struggle with abstract content.

Research has shown that students exposed to computer simulations in science education often perform better than those taught through conventional means. For instance, Smetana and Bell (2012) noted that computer simulations help enhance conceptual understanding, engagement, and retention of knowledge. This is especially true when they are used together with inquiry-based learning. Similarly, de Jong and van Joolingen (1998) found that simulations are particularly effective when students are allowed to explore, experiment, and receive feedback in a controlled digital environment.

One of the key advantages of simulations over traditional teaching is their ability to provide repeated practice without the constraints of physical resources. In conventional classrooms, practical activities are often limited due to inadequate laboratory facilities, a lack of materials, or safety concerns. Computer simulations can replicate these experiments virtually, offering learners unlimited opportunities to explore scientific concepts (Makransky et al., 2019). This not only democratises access to practical science education but also supports differentiated instruction by accommodating various learning paces and styles.

However, it is important to acknowledge that simulations are not without limitations. Their effectiveness depends heavily on the design of the software, the availability of technological infrastructure, and the teacher's ability to integrate them effectively into the curriculum (Hmelo-Silver et al., 2007). In settings where access to electricity, computers, or internet connectivity is inconsistent, traditional methods may remain the only viable instructional option (Ghana Education Service, 2019).

Furthermore, traditional teaching offers structured and sequential instruction, which can be beneficial for laying a foundation before transitioning to more exploratory learning methods. Prince and Felder (2006) argue that the optimal learning experience often results from a hybrid model that combines traditional teaching for content coverage with computer simulations for application and engagement.

In summary, while traditional teaching methods provide foundational structure and are widely used due to practicality, computer simulations offer an enriched learning experience that promotes higher-order thinking and deeper conceptual understanding. The integration of both approaches, where feasible, may yield the most effective educational outcomes in genetics instruction.

2.6 Effectiveness of Computer Simulations in Teaching and Learning

Computer simulations have been widely acknowledged as powerful instructional tools that can transform the teaching and learning process, especially in science education. Their effectiveness lies in their ability to simplify abstract concepts, provide visual representations, and create interactive environments that promote active student engagement. According to Rutten et al. (2012), simulations support the development of inquiry-based learning skills by allowing students to manipulate variables and observe outcomes in real-time. This process enhances conceptual understanding and promotes deeper learning, particularly in subjects like biology, where microscopic or abstract processes are difficult to observe directly.

In the context of genetics education, computer simulations help students visualise processes such as DNA replication, meiosis, and genetic inheritance patterns that are often difficult to grasp through traditional lecture methods. A study by Smetana and Bell (2012) emphasised that computer simulations improve students' scientific reasoning and understanding by offering opportunities to experiment with biological models in a risk-free environment. This flexibility allows students to repeat experiments, test hypotheses, and receive instant feedback, which can significantly improve learning outcomes.

Furthermore, research conducted by Babateen (2021) in secondary schools demonstrated that students who were taught using computer simulations performed significantly better than those who received instruction through conventional methods. The study found that simulations not only enhanced academic achievement but also increased learners' motivation and interest in science subjects. Similarly, Asuamah et al. (2020) observed that when simulations were integrated into biology lessons in Ghanaian senior high schools, students showed improved comprehension and retention of genetic concepts compared to those in non-simulation classrooms.

Despite these benefits, there are challenges associated with implementing computer simulations in classroom settings. Technical limitations, lack of teacher training, and limited access to digital devices may hinder the effective use of simulations, particularly in resource-constrained environments (Yadav & Singh, 2020). Nevertheless, when these obstacles are addressed, simulations offer a promising alternative to traditional instruction by fostering learner autonomy, enhancing visualisation of complex ideas, and encouraging exploratory learning.

In summary, numerous studies support the effectiveness of computer simulations as an innovative teaching strategy that enhances students' understanding, engagement, and academic performance in science education. The positive outcomes reported across different educational settings reinforce the need to explore their impact in new contexts such as the Nzema East Municipality, where such evidence is still limited.

2.7 Studies on 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, Boateng and Ofori (2021) conducted a quasi-experimental study in Ghana to compare the performance of students taught genetics using computer simulations with students 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 Tsai and Tsai (2020) used interactive genetics simulations among secondary school students in Taiwan. Their findings revealed that students improved in academic performance and 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 most 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.

2.8 Gender Disparities in the Use of Computer-Based Instruction in Science Education

Recent investigations have continued to examine gender-related differences in computer use and attitudes, indicating that despite notable progress toward achieving equity in technology engagement, significant disparities remain. Male students often report higher confidence and more positive attitudes toward computers compared to female students, especially at secondary and tertiary education levels (Kim & Shin, 2022; Lopez & Akter, 2023). For example, Kim and Shin (2022) found that while access to computers has become more equal in early education stages, boys still exhibit greater self-efficacy and interest in computer-related tasks by middle school. Similarly, Lopez and Akter (2023) reported that male university students perceive themselves as more competent users of digital technologies and engage more frequently in advanced computing activities than females.

However, some studies suggest a narrowing gender gap in the use and attitudes towards computer-based technology in science education in early schooling years. In a large-scale study involving elementary students, Hu (2024) found minimal differences between boys and girls in terms of computer usage frequency and enjoyment. Yet, these differences re-emerged at higher grade levels, with boys displaying more positive attitudes and greater engagement with computing (Hu, 2024; Silva & Costa, 2020). The findings suggest that social and educational factors during adolescence may contribute to the divergence in the use and attitude towards computer-based lesson delivery between genders.

At the university level, gender differences persist but show signs of change depending on discipline and context. Research by Patel and Singh (2024) highlighted that male students in STEM fields tend to report higher computer self-efficacy and more frequent use of digital learning tools than female peers. However, in non-STEM fields, gender differences were less pronounced. This suggests that the field of study influences attitudes and usage of technology. Moreover, studies focused on online learning environments during the COVID-19 pandemic found that female students faced more challenges related to digital confidence and access, which affected their attitudes toward computer-based learning (Ahmed & Bakar, 2021; Kumar et al., 2023).

Overall, current literature emphasises the need to address gender-specific barriers and promote inclusive technology education to foster equal computer confidence and usage across genders at all educational levels.

2.9 Empirical Evidence Supporting the Use of Computer Simulations in Genetic Instruction

A growing body of empirical research supports the effectiveness of computer simulations in enhancing student learning, particularly in complex science topics such as genetics. Rutten et al. (2012) conducted a comprehensive meta-analysis, which concluded that simulation-based instruction improves learning outcomes in science. Their findings showed that simulations help students explore, interactively and accessibly, abstract concepts such as genetic inheritance, molecular processes, and DNA mechanisms, leading to better understanding and retention.

Similarly, Chernikova et al. (2020) carried out a large-scale meta-analysis in higher education settings and found that students taught with simulations consistently outperformed those taught with conventional methods. They argued that the visualisation and interactivity afforded by simulations foster active learning, real-time feedback, and inquiry-based exploration qualities, particularly beneficial when teaching topics like DNA replication and protein synthesis that are otherwise difficult to visualise using static diagrams or textbooks.

Mayer's (2005, 2009) cognitive theory of multimedia learning further explains why simulations are so effective. He posits that learners understand complex information more efficiently when it is presented through a combination of verbal and visual modes. In molecular biology, simulations such as animated DNA transcription and translation reportedly reduce cognitive overload by sequentially presenting information in a coherent and interactive format (Reference).

Empirical findings by Afify (2020) also support this view, showing that interactive video simulations significantly reduced cognitive load and improved knowledge retention among learners. This is especially relevant for the teaching of molecular genetics, where students must understand step-by-step processes like the unwinding of DNA, base pairing, and ribosomal translation.

Furthermore, de Jong and van Joolingen (1998) found that discovery-based learning environments, such as computer simulations, promote deep conceptual change. Their study showed that learners engaged in simulations are more likely to form accurate mental models, test hypotheses, and self-correct misconceptions all of which are essential when learning intricate processes like nucleic acid structure and protein synthesis.

However, Parong and Mayer (2018) caution that simulations must be well-designed and supported by instructional scaffolding. Without proper guidance, students might focus on superficial features rather than the core scientific concepts. Yet, when used effectively within a structured instructional setting, simulations can bridge gaps in understanding and significantly enhance learning outcomes.

In conclusion, empirical evidence from multiple studies strongly supports the use of computer simulations in teaching genetics. These tools are particularly effective in helping students grasp abstract molecular concepts, such as nucleotides, replication, and protein synthesis. When implemented with pedagogical care, simulations not only improve academic performance but also foster motivation, engagement, and long-term retention of scientific knowledge.

CHAPTER THREE

METHODOLOGY

3.0 Overview

This chapter outlines the methodological framework that guided the study. It describes the study area and explains the research paradigm that shaped the current investigation. It also discusses the research design, which is based on a quasi-experimental model used to explore the effectiveness of instructional approaches. Additionally, the chapter details the population studied, the sampling techniques employed, and the procedure used to determine the sample size. The chapter further presents a comprehensive account of the instruments used for data collection, including the steps taken to establish their validity and reliability. Finally, the chapter explains the procedures followed during data collection and describes how the collected data were systematically analysed to address the research objectives.

3.1 Study Area

The research took place in the Nzema East Municipality, an administrative district located in Ghana's Western Region. Established in 2008 after being carved out of the larger Nzema District, the municipality has Axim as its administrative capital. It lies between latitudes 4°40'N and 5°20'N and longitudes 2°05'W and 2°35'W, covering an estimated land area of 2,194 square kilometres (Ghana Statistical Service, 2021). It shares boundaries with the Ahanta West Municipality to the east, the Ellembelle District to the west, and the Gulf of Guinea to the south. The location of the municipality along the coast enables the population to engage in various economic activities, including fishing, farming, and petty trading.

The area is predominantly rural and agrarian, with the major occupation being cocoa, coconut, oil palm, cassava, rubber plantation and plantain cultivation. Fishing likewise serves as a significant activity, especially in coastal towns such as Axim, Apewosika, and Brawire. Nzema East has a humid tropical climate with two rainy seasons, which sustains year-round agricultural productivity.

Within the Nzema East Municipality, there are four public Senior High Schools and a single private Senior High School. The public Senior High Schools are Kwame Nkrumah Senior High School at Nsein, Axim Girls' Senior High School in Axim, Gwiraman Senior High School in Bamiankor, and the Axim TVET Institute in Axim, offering technical and vocational programmes. The only private Senior High School is Manye Academy Senior High School, also located in Axim. All these schools include Biology as an elective subject and make a significant contribution to second-cycle science education in the municipality (Ghana Statistical Service 2021).

3.2 Research Paradigm

A research paradigm is 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 to describe a distinctive way of thinking within scientific inquiry.

In educational research, the term is often used to represent a researcher’s worldview, an overarching perspective that influences how knowledge is conceptualised and how data are interpreted (Mackenzie & Knipe, 2006).

A researcher's worldview covers their perspective, values, and assumptions about reality and knowledge. This set of beliefs acts as a lens through which he or she understands the research problem and guides the way data are collected, analysed, and interpreted. In this regard, Willis (2007) describes a research paradigm as an all-encompassing system of beliefs or a conceptual framework that informs research activities and professional practice. It reflects the researcher’s view on what is considered valid knowledge and the appropriate methods for acquiring it.

According to Lather (1986), a paradigm expresses the researcher’s position regarding the world they live in and aspire to influence. It is a manifestation of deep-seated theoretical principles. It influences how one understands and engages with the world. Similarly, Hughes (2010) describes a paradigm as a particular lens or way of viewing the world, which shapes the framing of research questions and influences the researcher’s thought process throughout the study. Fraser and Robinson (2004) also point out that paradigms embody agreed assumptions about the existence of problems and the acceptable methods of investigating them.

Guba and Lincoln (1994), recognised authorities in the field, define a paradigm as a fundamental set of beliefs or worldview that underpins research choices and actions. In the same vein, Denzin and Lincoln (2000) describe paradigms as human constructs that outline the fundamental premises from which researchers operate to derive meaning from data.

Drawing on these perspectives, it can be concluded that a research paradigm is not just a theoretical concept but a vital framework that embodies the researcher's worldview and belief system. It informs all aspects of the research process, including the formulation of the research problem, the development of questions, the understanding of reality and knowledge, the choice of methodology, and the overall value ascribed to the research endeavour. Different perspectives or viewpoints guide the conduction of research, including positivism, post-positivism, interpretivism, pragmatism, constructivism, and transformative paradigms.

This research is anchored in 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. It 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. It is especially appropriate for quasi-experimental designs because it allows for both the assessment of causal effects and the exploration of contextual variables. Morgan (2007) affirms that pragmatism enables researchers to utilise both quantitative and qualitative approaches to gain a fuller understanding of educational phenomena. This is critical in studies such as the present one, which examines not only the academic performance of students taught genetics using computer simulations compared to those taught through conventional methods but also seeks to explore gender differences and student perceptions regarding the instructional approach.

Furthermore, adopting a pragmatic stance allows the researcher to recognise the importance of both objective data and subjective insights. Creswell and Plano Clark (2011) emphasise that the strength of pragmatism lies in its capacity to bridge the gap between numerical analysis and the exploration of lived experiences. In this study, the quantitative aspect focuses on achievement differences, while the qualitative component captures students' attitudes and feedback, providing a well-rounded evaluation of the instructional strategy.

In summary, the pragmatic paradigm provides the necessary flexibility to address the multifaceted nature of teaching and learning within authentic educational settings, particularly in environments with resource limitations such as the Nzema East Municipality. Its focus on practical solutions and accommodation of multiple data sources makes it an ideal fit for the objectives and design of this research.

3.3 Research Design

Since this study involved the collection of both quantitative and qualitative data, a mixed methods approach was employed. As Creswell (2003) explains, mixed methods research entails gathering, analysing, and integrating quantitative approaches (for example, surveys or experiments) with qualitative approaches (such as interviews or focus groups). This design capitalises on the strengths of each method to offer a more comprehensive understanding of the issue under investigation. It is particularly valuable when researchers seek to confirm results across different methods or when they wish to elaborate on, extend, or clarify the findings of one approach through another. Using mixed methods also allows for a wider and deeper exploration of the research problem, resulting in more rounded outcomes. A key advantage of this approach is its ability to offset the limitations of both quantitative and qualitative strategies, while providing richer insights than either could on its own. However, it does present challenges, including the difficulty of reconciling conflicting findings and the considerable time and resources required to design and implement such research.

Creswell (2012) lists several mixed methods designs that researchers can employ, including exploratory sequential, convergent parallel, embedding, transformational, explanatory sequential, and multiphase designs. The present study utilised an embedded mixed methods approach, wherein the qualitative data complements the quantitative data (Creswell, 2012).

An embedded mixed methods design was adopted for this study (Fig. 3.1). The quantitative component was used to determine the effectiveness of the computer simulation model on students' achievement in genetics, while the qualitative component explored students' perceptions of the simulation approach, thereby complementing and supporting the quantitative findings.

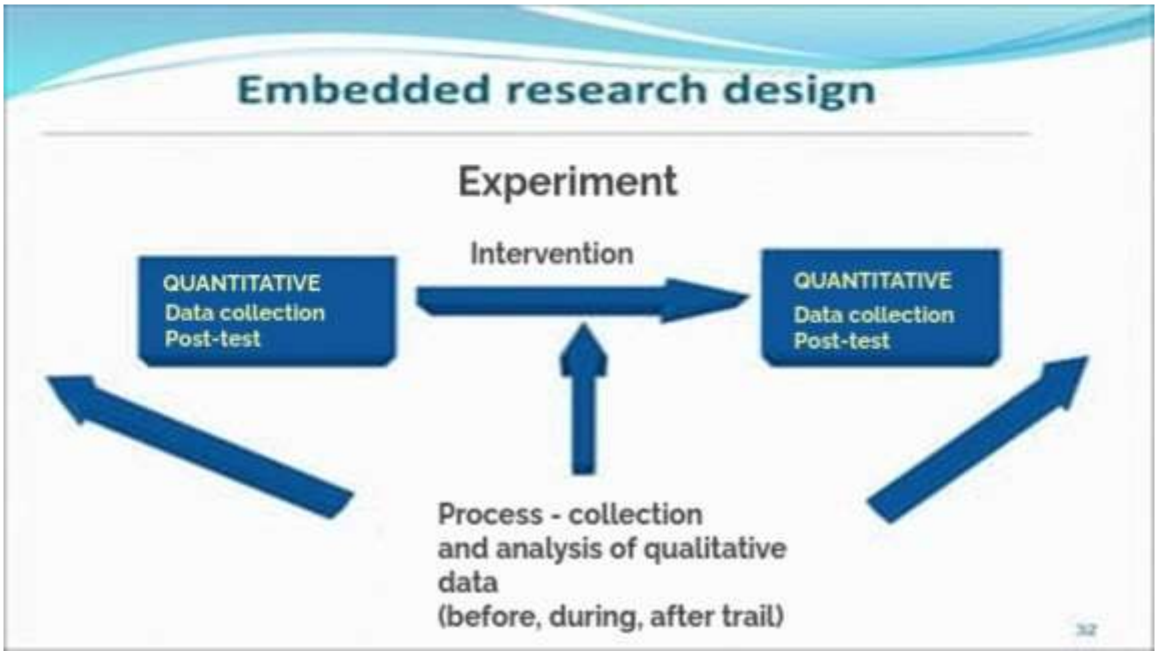

Figure 3.1: The Embedded Mixed Method Design (Creswell & Clark, 2018)

With the quantitative approach, a quasi-experiment, that is, a pre-test/post-test non-equivalent group approach was used. This is because, students were not assigned randomly into groups, but rather, intact classes were used where there was the possibility that there were dissimilarities in the groups that were used for the study (Kurt,2017). Because intact classes were used, the study's internal validity may not be as strong as in true experimental designs where participants are randomly assigned to groups (St. Clair et al., 2014). Another limitation of this design is the possibility of interaction between groups, which could threaten internal validity. This concern was addressed by selecting intact classes from different schools located in separate towns.

On the qualitative side, semi-structured interviews were conducted to explore students' views on the use of computer simulations as a teaching strategy for the group assigned to that method. These perspectives provided the qualitative data for the research. The purpose of combining the two approaches was to obtain deeper insights into the extent to which computer simulation packages could influence Senior High School students' performance in molecular genetics, as well as their attitudes towards the method as a teaching tool (Hanson et al., 2005; Creswell, 2012). Within an embedded mixed methods design, researchers typically combine quantitative and qualitative evidence throughout the investigation, leading to a fuller and more integrated understanding of the research problem. While this design offers notable strengths, it also presents certain limitations. It requires a substantial length of time to complete all data collection given in the two separate phases.

3.4 Population of the Study

In educational research, the term population denotes the total set of individuals, events, or elements that a researcher intends to investigate and to which the study's conclusions may be generalised (Creswell & Creswell, 2018). Within this context, a distinction is typically drawn between the target population and the accessible population. The target population comprises the full group that satisfies the criteria aligned with the study's aims, whereas the accessible population refers to the subset of that group which the researcher can realistically approach and include in the research (Fraenkel et al., 2019).

In this research, the target population comprises all Form Three Biology students in Senior High Schools within the Nzema East Municipality who are studying genetics as part of the elective biology curriculum. These students were considered appropriate because genetics is introduced in their year of study, making them suitable for investigating the impact of different instructional strategies on their academic performance.

The accessible population consisted of Form Three Biology students drawn from three public Senior High Schools within the municipality: Kwame Nkrumah Senior High School, located at Nsein, Axim Girls' Senior High School in Axim, and Gwiraman Senior High School situated at Bamiankor. These schools were purposefully selected due to their offering of biology as an elective subject, their geographical accessibility, and their willingness to participate in the study. The inclusion of both single-sex and co-educational institutions also allowed the study to explore gender-related performance dynamics in the context of computer simulations-based instruction.

Defining both the target and accessible populations clearly ensures that the sampling process is aligned with the study's goals and supports the reliability and applicability of its findings. As Cohen et al. (2018) emphasise, specifying the population framework is a critical step in ensuring the validity of educational research.

3.5 Sampling and Sampling Procedure

Sampling is a fundamental process in research that involves selecting a portion of a population to participate in a study to draw conclusions that can be generalised to the entire group. According to Creswell and Creswell (2018), 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 (Fraenkel et al., 2019). Researchers must therefore adopt sampling strategies that are not only practical but also methodologically sound.

There are two broad categories of sampling techniques: probability sampling and non-probability sampling. Probability sampling gives each member of the population an equal chance of being selected, thereby increasing the likelihood that the sample accurately reflects the population (Cohen et al., 2018). Probability sampling techniques include simple random sampling, stratified sampling, systematic sampling, and cluster sampling.
In contrast to probability sampling, non-probability sampling does not provide each individual in the population with an equal likelihood of selection. Instead, participants are chosen according to specific attributes or requirements connected to the study's purpose. Typical forms of this approach include purposive, convenience, quota, and snowball sampling (Etikan et al., 2016). Purposive sampling, in particular, enables the researcher to intentionally select individuals who display characteristics vital to the research, making it highly effective for collecting focused data (Palinkas et al., 2015).

A multistage sampling procedure was employed to guarantee both the suitability and representativeness of the sample for this research. During the preliminary stage, simple random sampling was applied to identify three public senior high schools in the Nzema East Municipality. Each school had an equal likelihood of being chosen, resulting in the inclusion of Kwame Nkrumah Senior High School, Axim Girls' Senior High School, and Gwiraman Senior High School. This method ensured fairness and minimised selection bias at the institutional level. In the second stage, purposive sampling was applied to include all third-year Biology students from the selected schools. This was necessary because the study focused on a topic in Genetics, a core component of the biology curriculum, and therefore required participants actively engaged in the subject. This approach enhanced the relevance of the sample to the research focus.

In the third stage, in each school, simple random sampling was applied to select two intact classes from among the third-year Biology learners. One class from each school was assigned to the experimental group, and the other to the control group, preserving the natural classroom environment essential for maintaining ecological validity in the quasi-experimental research design.

The categorisation of groups into experimental and control conditions was determined by the performance of the intact classes on a pre-test, referred to as the 'Students' Knowledge in Genetics Test' (SKGT). This test was administered to all participants within their respective classrooms at the selected schools. The average scores achieved by each intact class on the SKGT were used as the criterion for grouping. Classes with lower mean scores were assigned to the experimental groups, whereas the class with the highest mean score was designated as the control group. This arrangement aimed to investigate whether students with initially lower academic performance would derive greater benefit from the computer simulation-based instructional strategy compared with the higher-performing class receiving conventional instruction. The mean scores of the intact classes are presented in Table 3.1.

Table 3.1: Mean Scores on SKPT of Intact Classes Included in the Study

School	Class	Group	Mean Score
Kwame Nkrumah Sen High Sch	3 Science B	Exp. Group 1	9.71
	3 Science C	Control Group 1	12.55
Axim Girls Senior High School	3 Home sc1	Exp. Group 2	11.35
	3 Home sci E2	Control Group 2	12.83
Gwiraman S.H.S	3Science	Exp Group 3	8.62
	3 Home sci 1	Control Group 3	9.85

In the final stage, systematic random sampling was conducted to select ten students from each experimental group for qualitative interviews. This was done using class registers: every third student was chosen from Kwame Nkrumah SHS (31 students), every sixth student from Axim Girls' SHS (57 students), and every third student from Gwiraman SHS (32 students), until 10 students were selected from each group. This ensured balanced and proportionate representation of student perspectives in the qualitative data.

Altogether, the sample consisted of 230 senior high school students drawn from six 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, 174 were females, accounting for 76%, while 56 were males, representing 24%. This gender distribution reflects the inclusion of a girls-only school (Axim Girls' SHS) and female-only classes (3 H.E) in the sample. The arrangement of participants within the study sample is outlined in Table 3.2 below.

Table 3.2: 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
	3SC C (Control Group 1)	22(62.86)	13(37.14)	35
Axim Girls Senior High School	23 H. E1 (Exp. Group)		57 (100)	57
	3 H. E2 (Control Group 2)		45 (100)	45
Gwiraman S.H.S	3SC (Exp Group 3)	20(62.50)	12(37.50)	32
	3 H.E (Control Group 3)		30(100)	30
		56 24.00)	174 (76.00)	230

3.6 Research Instruments

A research instrument refers to any tool or technique used by the researcher to collect, measure, and analyse data relevant to the research objectives. These instruments are essential for ensuring the validity, reliability, and consistency of the information gathered

(Cohen et al., 2018). According to Creswell and Creswell (2018), the choice of instrument depends on the nature of the study, the type of data required, and the research design employed.

There are various types of research instruments commonly used in educational research. These include tests, questionnaires, interviews, observation schedules, and document analysis guides (Fraenkel et al., 2019). Quantitative instruments such as standardised tests and structured questionnaires are often used in experimental and quasi-experimental studies to generate measurable data (Hasan, 2024). On the other hand, qualitative instruments like interviews and open-ended surveys help gather detailed insights into participants' experiences and perspectives (Jain, 2021).

A mixed-methods approach was employed in this study, requiring the utilisation of both quantitative and qualitative data collection instruments. The quantitative data were gathered through two researcher-designed tests: The Students' Knowledge in Genetics Test (SKGT) and the Students' Achievement in Genetics Test (SAGT). The SKGT functioned as a pre-test, intended to evaluate students' prior knowledge of genetics concepts prior to 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 comprised 10 multiple-choice items with four answer options and five structured response questions designed to assess comprehension, application, and interpretation of genetics concepts, for example, DNA and RNA structure, DNA replication, and the formation of proteins. These instruments were designed based on the SHS Biology syllabus and reviewed by subject experts to ensure content validity.

In addition to the test instruments, a semi-structured 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 (2015), who advocates 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.

3.7 Validity of the Instruments

To ensure the content validity of the research instruments, the Students' Knowledge in Genetics Test (SKGT) and the Students' Achievement in Genetics Test (SAGT), which served as the pre-test and post-test respectively, were reviewed by a senior lecturer, the researcher's supervisors, and three experienced senior high school Biology teachers. The reviewers assessed the test items for clarity, appropriateness of language, relevance to the genetics curriculum, adequacy in covering the content areas, 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 clearly worded, aligned with the study objectives, and capable of eliciting meaningful and insightful responses from participants.

3.8 Pre-testing of the Instruments

Both the SKGT and SAGT instruments were pre-tested to establish the reliability and clarity of the instruments before their administration in the main study. The pilot was conducted at Baidoo Bonsu Senior High Technical School, using an intact class of Form Three science students offering Biology as an elective. These students shared similar academic characteristics with the actual research participants but were excluded from the main study. They were deemed appropriate for the pre-testing of the instrument because they had already studied genetic concepts, making them capable of providing meaningful feedback on the items in both the pre-test and post-test instruments. Hertzog (2008) recommends a pre-testing sample size of between 10 and 40 participants per group for evaluating the appropriateness of research instruments. Consistent with this guidance, the instrument pre-testing involved all 42 students in the selected science class at Baidoo Bonsu Senior High Technical School.

3.9 Reliability of the Instruments

The reliability of the SKGT and SAGT was confirmed through pre-testing and the application of appropriate reliability analyses. Reliability refers to the extent to which a measurement instrument produces consistent and dependable results under similar conditions. For the objective test items, internal consistency was examined using Cronbach's alpha, with the SKGT yielding $\alpha = .79$ and the SAGT $\alpha = .84$. According to

George and Mallery (2018), these values reflect acceptable to good reliability, indicating that the objective items consistently measured students' achievement in genetics. For the essay test items, inter-rater reliability was employed to assess consistency, as scoring relied on examiner judgement. Inter-rater reliability measures the degree of agreement between two or more independent scorers assessing the same responses using a shared rubric (McHugh, 2012). Cohen's Kappa coefficient was used to determine this agreement, as it is suitable for ordinal or categorical data and accounts for agreement occurring by chance. The interpretation of Kappa values follows Landis and Koch's (1977) scale, which categorises agreement as poor (<0.00), slight (0.00–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), and almost perfect (0.81–1.00). Based on this scale, the SKGT essay items yielded k = 0.75, and the SAGT yielded k = 0.64, both indicating substantial agreement.

Collectively, these results demonstrate that both the objective and essay components of the SKGT and SAGT were reliable, producing consistent measurements of students' performance in genetics. This confirms the credibility of the data collected and supports the use of these instruments in the study.

3.10 Data Collection Procedure

The process of data collection 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 relevant educational authorities. The procedure involved seeking institutional permissions, familiarising participants with the study, administering pre- and post-test instruments, and conducting interviews with selected students.

3.10.1 Pre-Intervention Stage

In each of the chosen schools, this study period lasted for one week within the Nzema East Municipality, namely Kwame Nkrumah SHS, Gwiraman SHS, and Axim Girls SHS. Before visiting the schools, the researcher first visited the Municipal Director of Education to formally introduce the study and seek authorisation. This was done with an official introductory letter from the Department of Science Education, AAMUSTED-M, accompanied by a personal cover letter from the researcher. Upon receiving approval, the researcher proceeded to the schools with copies of the endorsed letters.

Three familiarisation visits were conducted at each school. During the initial visit, the researcher formally introduced himself to the school heads and requested permission to carry out the study. The objectives of the research, its anticipated duration, and the potential benefits for students, teachers, and the school community were discussed. Following this engagement, the school heads informed the relevant subject teachers and encouraged their cooperation and support.

The second visit involved discussions with the subject teachers. During this stage, copies of the elective Biology timetables were collected from each school to aid in planning the data collection process. Two intact elective Biology classes were selected from each school. Subsequently, the researcher met the selected classes and provided students with an explanation of the study's purpose and scope in their classrooms.

On the final visit at this stage, participants were given the Students' Knowledge in Genetics Test (SKGT) as a pre-test in their individual classrooms. The test administration was supported by the subject teachers. The mean scores obtained from the SKGT were used to allocate the groups. Classes that obtained lower mean scores were assigned to the experimental groups, whereas the class with the highest mean score was designated as the control group. This grouping approach was employed to investigate whether students in the lower-performing classes would demonstrate greater gains in achievement following exposure to the computer simulation-based instructional intervention.

3.10.2 Intervention Stage

The treatment phase of the research was conducted over seven weeks in each of the three selected senior high schools: Kwame Nkrumah SHS, Axim Girls' SHS, and Gwiraman SHS. The main aim of this phase was to evaluate the effect of computer simulations on improving Form Three Biology students' understanding of genetics. To reduce the likelihood of the Hawthorne effect, wherein participants may modify their behaviour due to awareness of being observed, the intervention was administered sequentially rather than simultaneously across the schools. This strategy not only prevented potential cross-school influence but also enabled the researcher to give focused attention to the process in each setting.

Although the original plan allocated six weeks for the intervention, an unanticipated interruption at Gwiraman SHS resulting from an inter-house athletics competition necessitated a one-week extension. Instructional sessions were briefly suspended and resumed afterwards to ensure completion of the scheduled lessons. All three schools received the same instructional content, derived from the senior high school Biology curriculum with emphasis on the genetic component. The lessons were integrated into normal classroom periods and were delivered by the researcher using interactive computer simulations, accompanied by guiding questions and group discussions.

To maintain consistency across sites, each experimental group was exposed to identical teaching materials, simulation software, instructional sequences, and assessment tools. Meanwhile, the control groups continued with conventional teacher-centred instruction, without the integration of computer simulations. The sequential delivery of the intervention, coupled with standardised implementation procedures, ensured instructional fidelity and reinforced both the internal validity and trustworthiness of the study outcomes.

3.10.2.1 Intervention Activities

The intervention phase focused on delivering selected genetics topics to Senior High School Form Three Biology students using two distinct instructional approaches. Students assigned to the experimental groups were taught through lessons that integrated computer simulations over a span of seven weeks. Key areas covered included DNA structure, patterns of inheritance, and genetic crosses. These lessons were interactive, facilitated by the teacher, and closely aligned with the official Biology curriculum. In contrast, the control groups received instruction on the same topics using conventional pedagogical methods, such as teacher-led lectures, textbook readings, and verbal explanations. This dual-approach design enabled the researcher to compare the relative effectiveness of simulation-based instruction with traditional teaching methods in enhancing students' conceptual understanding of genetics. Lesson plans for the topics of nucleic acids and DNA replication, developed for both the conventional and simulation-enhanced instructional formats, were presented (See Appendix E).

3.10.3 Post Intervention Stage

The post-intervention activities were carried out during the final week designated for data collection in the participating schools. Upon completion of the intervention in each school, the Students' Achievement in Genetics Test (SAGT) was administered to both the experimental and control groups. The test was facilitated by the subject teachers of the participating classes and was conducted within their regular classroom environments. This phase aimed to assess the impact of computer simulation-based instruction on the academic achievement of SHS 3 students in genetics.

In addition to the post-test, 10 students were selected from each experimental group using simple random sampling for a semi-structured interview. The selection was done using the class registers to ensure that each student had an equal chance of being chosen. The interviews aimed to explore students' experiences and perceptions of the use of computer simulations in learning genetics. This qualitative component served to complement the quantitative findings and offered deeper insights into the instructional impact of the simulation-based approach.

3.11 Data Analysis Procedure

Data collected from the achievement tests, specifically, the SKGT as pre-test and SKGT as post-test, and along with a semi structure interview guide were systematically organised and analysed using the Statistical Package for the Social Sciences (SPSS) version 26. Descriptive statistics such as frequencies, percentages, means, and standard deviations were used to summarise the demographic characteristics of participants and to provide an overview of students' academic performance. For inferential analysis, non-parametric statistical tests were employed due to violations of the assumption of normality in the test scores. To answer the first research question, which aimed to establish whether a significant difference existed in academic performance between students taught using the computer simulation instructional approach and those taught via the traditional method, Mann-Whitney U test was applied to both the pre-test and post-test scores.

In response to the second research question, which explored potential gender-based differences in academic performance among students in the experimental group, the Mann-Whitney U test was also employed to compare the pre-test and post-test scores of male and female students. To evaluate the effect of the computer simulation instructional approach on students' learning outcomes in genetics, the Wilcoxon Signed-Rank Test was used to analyse the differences between pre-test and post-test scores within the experimental group. Lastly, research question 4 was also analysed thematically, using transcribed data to determine how Senior High School students perceive the effectiveness of computer simulation-based instruction

An alpha level of 0.05 was adopted as the threshold for determining statistical significance. Additionally, effect sizes (r) were calculated to quantify the magnitude of observed differences. Interpretation of the effect sizes followed Cohen's (1988) guidelines, in which $r \approx 0.10$ represents a small effect, $r \approx 0.30$ a medium effect, and $r \geq 0.50$ a large effect. The sign of *r* (positive or negative) indicates the direction of the difference, while the magnitude (absolute value) reflects the strength of the effect (Field, 2018; Pallant, 2020).

3.12 Ethical Consideration

This study adhered to strict ethical standards to ensure the rights, privacy, and well-being of all participants were protected. Ethical approval was obtained from the Committee on Human Research, Publication and Ethics (CHRPE) with approval number CHRPE/AP/946/25. Permission was also sought from the Director of Education in the Nzema East Municipality, and the heads of the participating schools. Informed consent was obtained from all participating students, who were fully briefed on the purpose of the study, the procedures involved, and their right to withdraw at any time without penalty.

Confidentiality and anonymity were maintained throughout the study by assigning codes to participants and securely storing all data. Only the researcher and his supervisors had access to the collected information, which was used solely for academic purposes.

Additionally, the study ensured that no harm or discomfort was caused to the participants, and care was taken to respect cultural sensitivities and school regulations during data collection. Adherence to these ethical procedures not only protected participants but also strengthened the credibility and reliability of the research findings.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Overview

In this chapter, the results are presented and subsequently discussed on the effectiveness of computer simulations on senior high school students' understanding of genetics in Nzema East Municipality. The findings are given based on the research questions. They are based on data acquired from the participants, and assembled, sorted, coded, and analysed using descriptive and inferential statistics through the Statistical Package for the Social Sciences (SPSS) version 26. The findings are given based on the following study questions:

1. What is the academic performance between students taught genetics with computer simulation-based instruction and those taught with traditional methods?
2. What is the difference in the academic performance between male and female students taught using computer simulation-based instruction?
3. What is the effect of computer simulation-based instruction on students' performance in genetics?
4. What are students' perceptions of the computer simulation-based instruction in genetics?

4.1 Demographics of Respondents

Figure 4.1 depicts the distribution of the biology students from the three public SHSs who participated in the current study based on their gender. Of the 230 study participants, 76% (n= 174) were females, while 56 were males, representing 24%.

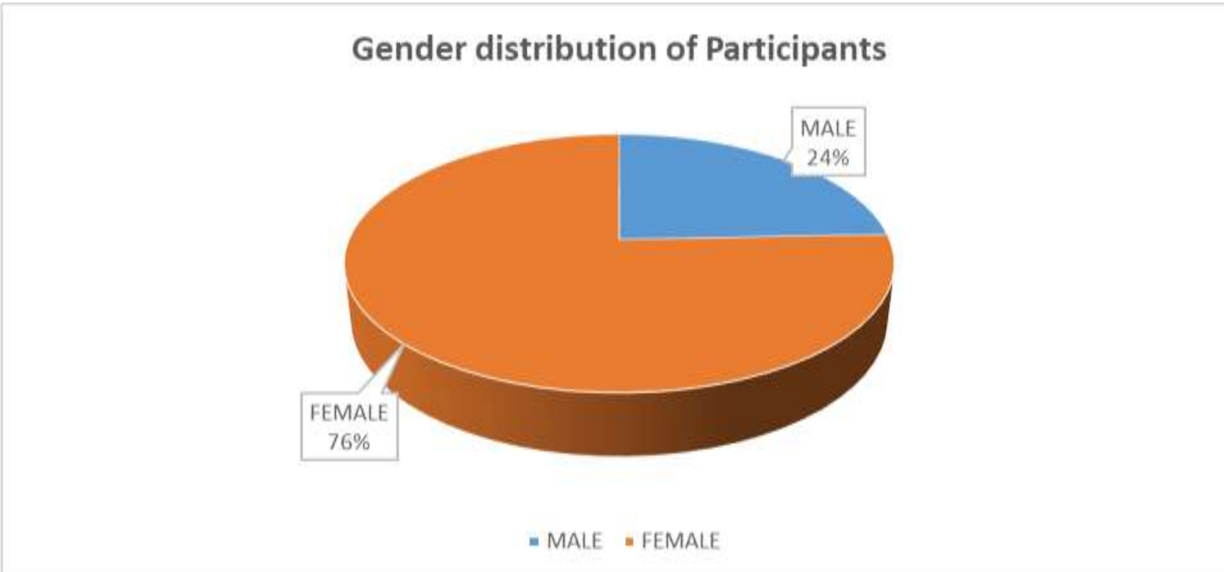

Figure 4.1: Gender distribution of Participants

4.2 Data Suitability

Prior to analysing the study's outcomes, normality tests were performed to ensure that the data were suitable. The findings are presented in the following subsection. 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. Normality tests were performed under the "null hypothesis that the data sets are normally distributed" (Pallant, 2011a). This indicates that the null hypotheses are rejected when the Kolmogorov-Smirnov test yields a p-value larger than 0.05. Table 4.1 presents the results of the normality tests.

Table 4.1: Results of Normality Tests for Students' Scores

Groups of Students	**Kolmogorov-Smirnov**[a]			**Shapiro-Wilk**		
	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		.001*	.897		.001*
Post-test of Experimental Group	.140	119	.001*	.960	119	.002*

a. Lilliefors Significance Correction

***Significant since p < 0.05**

Normality testing using the Kolmogorov–Smirnov and Shapiro–Wilk tests from Table 4.1 revealed significant results (p = .001, .002, .001, .001 and p = .005, .004, .001, .002 respectively), indicating that the student performance scores were not normally distributed. As a result, non-parametric methods such as Mann-Whitney U Test and Wilcoxon Signed Rank Test were used in subsequent analyses.

Research question 1: What is the academic performance between students taught genetics with computer simulation-based instruction and those taught with traditional methods?

A Mann-Whitney U test was conducted to compare the pre-test scores of students in the experimental group and the control group to serve as a baseline for comparing both groups (see appendix F).

Table 3.2: Mann-Whitney U Test on the Pre-test of both Groups

Groups	N	*U*	Mean rank	Z	*R*	*P*
Experimental Group	230	6047.50	120.10	-1.10	-0.07	0.27*
Control Group			110.48			

***Not significant since p > 0.05**

A Mann-Whitney U test was conducted to compare the pre-test scores of students in the experimental group (n = 120) and (n = 110) in the control group. Results indicated no statistically significant difference between the two groups on the pre-test, U = 6047.50, z = -1.10, p = 0.27, r = -0.07. This suggests that both groups were comparable in their prior knowledge of genetics before the intervention.

4.3.1 Differences in the Academic Performance between the Experimental and Control Group on their post-test

A Mann-Whitney U test was conducted to compare the post-test scores of students in the experimental group and the control group to determine the differences among the groups.

Table 4.3: Mann-Whitney U Test on the Post-test of both Groups

Groups	N	*U*	Mean Rank	Z	*R*	*P*
Experimental Group	230	2672.00	148.23	-7.82	-0.52	0.001*
Control Group			79.79			

***Significant since p < 0.05**

A Mann-Whitney U test (Table 4.3) was conducted to examine the post-test performance of students in the experimental and control groups. The test revealed a statistically significant difference in favour of the experimental group, U = 2672.00, z = -7.82, *p* =0.001, r = -0.52. The mean rank of the experimental group (148.23) was notably higher than that of the control group (79.79), indicating that students who were taught using computer simulations outperformed those taught using traditional methods. The effect size (r = -0.52) suggests a large effect according to Cohen's criteria (Fritz et al., 2011).

Research question 2: What is the difference in academic performance between male and female students taught using computer simulation-based instruction

A Mann-Whitney U test was performed on male and female students' pre-test scores within the experimental group to serve as a baseline for comparing their prior knowledge (Table 4.4).

Table 4.4: Mann-Whitney U Test Results on the Pre-test of Gender

Groups	**N**	***U***	**Mean Rank**	**Z**	***R***	***P***
Female	120	1200.50	62.51	-1.10	-0.10	0.28*
Male			54.73			

***Not significant since p > 0.05**

The Mann-Whitney U test comparing male and female students' pre-test scores within the experimental group showed no significant difference, U = 1200.50, z = -1.10, p = 0.28, r = -0.10. Female students had a slightly higher mean rank (62.51) than males (54.73), but the difference was not statistically meaningful.

4.4.1 Differences in Academic Performance of Male and Female Students in the Experimental Group on their post-test

A Mann-Whitney U test was performed on male and female students' post-test scores to determine if there is a significant difference (Table 4.5).

Table 4.5: Mann-Whitney U Test Results on the Post-test of Gender

Groups	N	*U*	Mean Rank	Z	*R*	*P*
Female	120	1679.50	57.13	1.81	0.17	0.07*
Male			70.18			

***Not significant since p > 0.05**

A Mann-Whitney U test on the post-test scores revealed no statistically significant gender difference, U = 1679.50, z = 1.81, p = 0.07, r = 0.17. Although males had a slightly higher mean rank (70.18) than females (57.13), the result was not statistically significant at the conventional alpha level of .05. The effect size was small (Fritz et al., 2011).

Research question 3: What is the effect of computer simulation-based instruction on students' performance in genetics?

A Wilcoxon Signed Rank Test was used to assess changes in students' performance in the experimental group before and after receiving instruction via computer simulation (Table 4.6).

Table 4.6: Wilcoxon Signed Rank Test Results on the Effect of the Computer Simulation

Groups	N	Test Statistic	Mean	Z	*R*	*P*
Pre-test	120	7260.00	8.80	9.52	0.87	0.001*
Post-test			23.30			

***Significant since p < 0.05**

The test results from Table 4.6 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 4: What are students' perceptions of the computer simulation-based instruction in genetics?

This research question sought to determine how students taught using the computer simulations-based instruction perceived its effectiveness. A face-to-face, semi-structured interview conducted with 15 students showed 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 4.7 with explanations and representative statements from students (all names are pseudonyms).

Table 4.7: Thematic presentation of Student's perception on the Computer simulation-based instruction

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

4.6.1 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 that:

"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."

4.6.2 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 in behaviours associated with enhanced academic motivation and improved outcomes.

Mavis, a student who performed at a below-average level 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."

4.6.3 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, for example DNA replication, transcription of RNA, and the synthesis of proteins. 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 about how simulations supported his retention of detailed processes:

"Protein synthesis was clearer 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."

4.6.4 Theme 4: Engagement and Interactivity

Students who achieved 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 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."

4.6.5 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."

4.7 Discussion

4.7.1 Academic Performance of Students taught with Computer Simulation-based Instruction and those taught with those with traditional methods

The findings of the current study showed that students taught with computer simulations performed significantly better than those taught with traditional instructional methods. This result is consistent with the growing body of research emphasising the benefits of simulation-based learning in science education. Rutten et al. (2012) and Vidzro (2018), for example, found that computer simulations promote conceptual understanding by allowing learners to visualise and manipulate variables in complex systems like genetics. The visual and interactive nature of simulations can reduce cognitive load and enhance learner engagement and retention (Afıfy, 2020). Moreover, Chernikova et al. (2020) conducted a comprehensive review and concluded that students using simulations often outperform peers taught through traditional instruction. Their findings indicate that simulations encourage inquiry-based learning, support hypothesis testing, and provide immediate feedback, all of which enhance understanding of scientific phenomena.

In the context of genetics education, simulations allow students to experiment with genetic crosses, mutations, and inheritance patterns; processes that are abstract and often difficult to grasp through conventional teaching. The significant difference found in this study (U = 2672.00, *p* = 0.001, r = -0.52) with a large effect size underscores the transformative potential of educational technology in enhancing learning outcomes. However, not all studies have found such positive outcomes. Some researchers argue that simulations may not always lead to better academic performance, especially if not properly integrated into instruction. Parong and Mayer (2018) observed that students may become distracted by the visual elements of simulations, focusing more on the animation than the underlying scientific principles. Similarly, Moon (2023) cautioned that without proper scaffolding, students might develop misconceptions due to over-simplified models presented in simulations. These opposing views suggest that while simulations can be powerful tools, their success depends on pedagogical design, teacher facilitation, and alignment with curriculum objectives. In this study, the significant improvement in performance among the experimental group implies that these conditions were likely met, highlighting the effectiveness of the intervention.

4.7.2 Academic Performance of Male and Female Students Taught using Computer Simulation Approach

The results of the current study showed no statistically significant difference between male and female students in both pre-test and post-test scores within the experimental group. Although males had slightly higher post-test mean ranks, the difference was not significant (U = 1679.50, *p* = 0.07), suggesting that both genders benefited equally from the simulation-based instruction. This finding supports the view that gender does not inherently influence the effectiveness of computer-based learning tools. For instance, Oladejo et al. (2023) concluded that when both male and female students are given equal access and orientation to simulation tools, their learning outcomes are generally comparable. Similarly, Cheruiyot et al. (2023) found that computer-assisted instruction in biology produced significant learning gains among both male and female students, with no notable gender disparities.

From a theoretical standpoint, the gender neutrality of simulation-based instruction can be explained by the Universal Design for Learning (UDL) framework, which advocates for multiple means of representation and engagement to cater to diverse learners (Sanguinetti, 2024). Simulations appeal to various learning styles and reduce the dependency on linguistic or mathematical skills, which may traditionally favour one gender over another. On the contrary, some studies have reported gender differences in technology-based learning. Research by Kay et al. (2017) indicated that male students tend to have more favourable attitudes towards simulations and may engage with them more frequently, potentially leading to better outcomes. However, these differences often diminish when instructional supports are equitable and when female students receive sufficient encouragement and exposure to the technology (Wang & Degol, 2017). Given the mixed findings in the literature, the absence of gender-based performance differences in this study suggests that the instructional environment was inclusive and well-structured, providing equal learning opportunities for both sexes.

4.7.3 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 the learning of genetics. The cognitive theory of multimedia learning (Clark & Mayer, 2024) 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 (Vygotsky, 1978). 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.

4.7.4 Students' Perceptions of the Computer Simulation Instructional Approach

The findings of the present study indicate that the use of computer simulations substantially improved students' comprehension of complex genetic concepts, including the structures of DNA and RNA, replication, and protein synthesis. Students reported that simulations helped make abstract content more tangible through animations, interactivity, and real-time feedback. This not only improved conceptual clarity but also increased students' academic confidence and performance. Many students transitioned from memorising steps to genuinely understanding biological processes, which aligns with Knoster (2021) cognitive theory of multimedia learning. The interactive nature of simulations fostered deeper engagement, allowing students to actively participate in their learning, consistent with the findings of Choi et al. (2017) on discovery-based science education.

In addition to conceptual understanding, simulations also boosted student motivation, retention, and their ability to relate genetic content to real-life contexts. Students expressed renewed interest in biology, with some even indicating aspirations to pursue genetics further. The lessons became more meaningful as learners could visualise the role of DNA in health, heredity, and protein formation, supporting the importance of real-world connections in learning. These improvements in engagement and motivation are reflective of self-determination theory, which highlights the impact of learner autonomy and interest on academic outcomes (Rigby & Ryan, 2018). Overall, the use of computer simulations transformed the classroom experience from passive reception to active, student-centred learning.

CHAPTER FIVE

SUMMARY, CONCLUSIONS, RECOMMENDATIONS, AND SUGGESTIONS FOR FURTHER RESEARCH

5.0 Overview

This section summarises the significant findings derived from the analysis of data in the preceding chapter. It draws conclusions based on the results, highlighting the impact of computer simulations on Senior High School students' understanding of genetics. The chapter further provides recommendations for educators, policymakers, and researchers, aimed at enhancing science instruction through the integration of digital tools. Lastly, it outlines suggestions for future research to build upon the insights gained from this study.

5.1 Summary of the Findings

This study set out to evaluate the effectiveness of computer simulations in enhancing Senior High School students' understanding of genetics in the Nzema East Municipality. The research employed an embedded mixed-method design, incorporating both quantitative and qualitative data. Three public Senior High Schools were selected, involving a total of 230 Biology students. The participants were divided into experimental and control groups, with the experimental group receiving instruction through computer simulations while the control group was taught using traditional methods.

The study was guided by four research questions: (1) What is the academic performance between students taught genetics with computer simulation-based instruction and those taught with traditional methods? (2) What is the difference in the academic performance between male and female students taught using computer simulation-based instruction? (3) What is the effect of computer simulation-based instruction on students' performance in genetics? (4) What are students' perceptions of the computer simulation-based instruction in genetics?

Quantitative data were analysed using non-parametric statistical methods, specifically, the Mann-Whitney U and Wilcoxon Signed-Rank tests, due to violations of the normality assumption. Qualitative data were obtained through semi-structured interviews with students from the experimental group and were subjected to thematic analysis.

5.2 Summary of key Findings

1. No statistically significant difference was observed between the experimental and control groups on the pre-test, suggesting both groups were at a similar starting point in terms of their prior knowledge in genetics.
2. Post-test analysis showed that students who received instruction through computer simulations significantly outperformed their peers who were taught traditionally, with a large effect size, indicating that the intervention was highly effective.

3. Gender-based comparisons within the experimental group revealed no significant differences in academic performance between male and female students, suggesting that the computer simulation strategy benefited both sexes equally.
4. There was a significant improvement in the performance of students within the experimental group between the pre-test and post-test, implying that the simulation-based instruction positively influenced learning outcomes.
5. Thematic analysis of students' perceptions revealed favourable attitudes towards the use of computer simulation. Students highlighted improved understanding of concepts, increased motivation, better retention, enhanced engagement, and the ability to relate genetics concepts to real-life situations.

5.3 Conclusions

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. Additionally, the lack of gender disparity suggests that the method provides equitable learning opportunities. 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 very effective instructional alternative but also a transformative strategy that fosters deeper learning, particularly in content-heavy and abstract science topics like genetics.

5.4 Recommendations

In view of the findings, the following recommendations are proposed:

1. It is advised that biology educators within the Nzema East Municipality adopt the integration of computer simulations in the delivery of genetics lessons, as part of ongoing efforts to enhance the academic performance of SHS students in the subject. To support this implementation, educational authorities in the municipality should coordinate capacity-building programmes such as seminars, training workshops, and professional conferences. These initiatives will equip teachers with the necessary skills and knowledge to effectively incorporate computer-based simulations into the teaching of Biology at the Senior High School level.
2. Educators in the Nzema East Municipality should continue using computer simulation tools in mixed-gender classrooms, as they create an inclusive environment that benefits both male and female learners equally while promoting active participation and collaboration among all students.
3. School authorities and the Ministry of Education in the Nzema East Municipality should prioritise the provision of digital teaching materials and offer professional development opportunities to enhance teachers' skills in implementing simulation-based instruction. Furthermore, steps should be taken to ensure that Senior High Schools with Nzema East Municipality are sufficiently equipped with the required infrastructure to support the effective implementation of computer simulation-based instruction.

4. Teachers in the Nzema East Municipality should continue integrating simulation tools in lessons and combine them with discussions and hands-on activities to sustain students' interest, deepen conceptual understanding, and encourage critical thinking and problem-solving skills

5.5 Suggestions for Further Studies

Several avenues for further research have been proposed based on the findings of this study. Firstly, future researchers may consider conducting a longitudinal study to explore the retention of genetics knowledge among students who are taught using computer simulations. While the current study revealed immediate academic gains, it remains unclear whether these improvements persist over an extended period. Investigating the long-term effects of simulation-based instruction will provide valuable insight into its sustainability and influence on lasting conceptual understanding. Secondly, further investigations are encouraged to assess the impact of computer simulations across different science topics and academic levels. The current study focused specifically on genetics within Senior High Schools. However, the nature of science education varies across subjects and stages. Exploring how simulations affect the learning of other biology topics, such as cell biology, evolution, or ecology, and whether similar outcomes are observed at the Junior High or tertiary level, will help to determine the wider applicability of this approach. Lastly, additional research could compare the effectiveness of computer simulations with other digital instructional tools, such as virtual laboratories, interactive videos, or educational games. Such comparative studies would help to identify which technologies offer the most significant benefits for improving student engagement and understanding in genetics. This would enable educators and stakeholders to make informed decisions about adopting the most effective digital resources in science instruction.

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APPENDICES

APPENDIX A

AKENTEN APPIAH – MENKAH UNIVERSITY OF SKILLS TRAINING AND ENTREPRENEURIAL DEVELOPMENT.

FACULTY OF SCIENCE EDUCATION

PRETEST DATA COLLECTING INSTRUMENT – STUDENTS' KNOWLEDGE IN GENETICS TEST" (SKGT)

Name of Participant: ……………………………………

School of participant: ……………......................................

Gender of Participant: …………… Class of Participant: ……… Duration: 45 mins

GENERAL INSTRUCTIONS: This test contains fifteen (15) questions grouped in two (2) sections, namely Sections A and B. Please answer ALL the questions in ALL the two (2) sections of the test.

SECTION A

MULTIPLE CHOICE QUESTIONS

INSTRUCTIONS: The following questions are followed by four (4) options lettered A to D. Find out the correct option and circle A, B, C or D to indicate your answer

1. Which of the following is the building block of nucleic acids?

A. Amino acids

B. Nucleotides

C. Monosaccharides

D. Fatty acids

2. Which nitrogenous base is found in RNA but not in DNA?

A. Adenine

B. Thymine

C. Guanine

D. Uracil

3. What type of bond holds the two strands of DNA together?

A. Ionic bonds

B. Covalent bonds

C. Hydrogen bonds

D. Peptide bonds

4. The sugar in a DNA nucleotide is:

A. Ribose

B. Deoxyribose

C. Glucose

D. Fructose

5. The process of DNA replication is described as:

A. Conservative

B. Dispersive

C. Semiconservative

D. Fragmented

6. Which of the following is a component of a nucleotide?

A. Phosphate group, sugar, nitrogenous base

B. Amino acid, sugar, nitrogenous base

C. Fatty acid, phosphate, sugar

D. Sugar, amino acid, phosphate

7. Which nitrogenous base pairs with adenine in DNA?

A. Uracil

B. Thymine

C. Cytosine

D. Guanine

8. Where in the cell does DNA replication occur?

A. Ribosome

B. Cytoplasm

C. Nucleus

D. Mitochondrion

9. What is the end product of transcription?

A. DNA

B. mRNA

C. tRNA

D. Protein

10. Which molecule brings amino acids to the ribosome during translation?

A. mRNA

B. tRNA

C. rRNA

D. DNA

Section B: Short-Answer Questions

11. Define DNA replication in one sentence. 4marks
12. List the four nitrogenous bases found in DNA. 4marks
13. Explain the difference between transcription and translation. 6marks
14. What is the significance of the start codon in protein synthesis? 4marks
15. Name the sugar found in RNA. 2marks

APPENDIX B

MARKING GUIDE FOR PRETEST (SKGT) ITEMS

1. B
2. D
3. C
4. B
5. C
6. A
7. B
8. C
9. B
10. B
11. DNA replication is the process by which a cell copies its DNA, producing two identical daughter strands from a single parent DNA molecule through a semiconservative mechanism. (4 marks: 1 for definition, 1 for mentioning copying, 1 for identical strands, 1 for semiconservative mechanism)
12. Adenine, Thymine, Guanine, Cytosine (4 marks: 1 mark per base)
13. Transcription is the process in which a segment of DNA is copied into a complementary mRNA molecule in the nucleus, using RNA polymerase to synthesise the mRNA. Translation, on the other hand, occurs in the cytoplasm at the ribosome, where the mRNA sequence is read to assemble amino acids into a polypeptide chain, forming a protein, with the help of tRNA and rRNA. The key differences are the location (nucleus vs. cytoplasm), the molecules involved (DNA to mRNA vs. mRNA to protein), and the

purpose (copying genetic information vs. synthesising proteins). (6 marks: 2 for describing transcription, 2 for describing translation, 2 for clear differences)

14. The start codon, typically AUG, signals the beginning of translation by indicating where the ribosome should start reading the mRNA to initiate protein synthesis. It also codes for the amino acid methionine, ensuring the correct starting point for the polypeptide chain. (4 marks: 2 for signaling translation start, 1 for specifying methionine, 1 for ensuring correct polypeptide formation)
15. Ribose (2 marks)

APPENDIX C

AKENTEN APPIAH – MENKAH UNIVERSITY OF SKILLS TRAINING AND ENTREPRENEURIAL DEVELOPMENT.

FACULTY OF SCIENCE EDUCATION

POST TEST DATA COLLECTING INSTRUMENT – STUDENTS' ACHIEVEMENT IN GENETICS TEST (SAGT)

Serial of Participant: ……………………………   Duration: 45mins

Gender of Participant: ……………………… Class of Participant: …………………

School of Participant: ……………………………………………………………………

GENERAL INSTRUCTIONS: This test contains fifteen (15) questions grouped in two (2) sections, namely Sections A and B. Please answer ALL the questions in ALL two (2) sections of the test.

SECTION A

MULTIPLE CHOICE QUESTIONS

INSTRUCTIONS: The following questions are followed by four (4) options lettered A to D. Find out the correct option and circle A, B, C or D to indicate your answer

1. What are the monomers that make up nucleic acids?

A. Polysaccharides

B. Nucleotides

C. Lipids

D. Amino acids

2. Which base is exclusive to RNA and not found in DNA?

A. Thymine

B. Adenine

C. Uracil

D. Cytosine

3. What type of bond connects the two strands in a DNA molecule?

A. Peptide bonds

B. Ionic bonds

C. Covalent bonds

D. Hydrogen bonds

4. Which sugar is found in the DNA structure?

A. Fructose

B. Ribose

C. Deoxyribose

D. Glucose

5. In a DNA double helix, which base pairs with guanine?

A. Cytosine

B. Thymine

C. Adenine

D. Uracil

6. Which enzyme joins Okazaki fragments during DNA replication?

A. Helicase

B. Ligase

C. Primase

D. DNA polymerase

7. If a DNA strand has the sequence 5' - GCT AAG TCC - 3', what would be the complementary mRNA sequence?

A. CGA UUC AGG

B. GCT AAG TCC

C. CGU UUC AGG

D. GCU AAG UCC

8. Which of the following best describes a codon?

A. A group of three nucleotides on mRNA

B. A group of three nucleotides on tRNA

C. A region of DNA that codes for a protein

D. An enzyme involved in protein synthesis

9. Which process ensures genetic continuity from one generation to the next?

A. Translation

B. Transcription

C. Replication

D. Mutation

10. What happens during the elongation stage of translation?

A. The ribosome assembles around the mRNA

B. Amino acids are added one by one to the growing polypeptide chain

C. The ribosome reaches a stop codon

D. The mRNA is synthesized from DNA

SECTION B

1. Differentiate between DNA and RNA based on their structure and function.

   2 marks

2. Describe the entire process of protein synthesis. 5 marks

3. Name the main components of a DNA molecule. 3 marks

4. Compare and contrast the roles of mRNA, tRNA, and rRNA in protein synthesis.

   6 marks

5. Describe the Watson and Crick model of DNA. 4 marks

APPENDIX D

MARKING GUIDE FOR POSTTEST (SAGT) ITEMS

1. B
2. C
3. D
4. C
5. A
6. B
7. A
8. A
9. C
10. B
11. Differentiate between DNA and RNA based on their structure and function (2 marks).

    Structure: DNA is a double-stranded molecule with deoxyribose sugar, while RNA is a single-stranded molecule with ribose sugar.

    Function: DNA stores genetic information, while RNA helps in protein synthesis by acting as a messenger (mRNA), bringing amino acids (tRNA), and forming ribosomes (rRNA).

12. Describe the entire process of protein synthesis (5 marks).

    Protein synthesis occurs in two main stages: transcription and translation. In transcription, DNA unwinds in the nucleus, and RNA polymerase synthesizes a complementary mRNA strand from a DNA template. The mRNA is then processed (capped, tailed, and spliced) and moves to the cytoplasm. In translation, the ribosome reads the mRNA sequence starting at the start codon (AUG), tRNA molecules bring specific amino acids matching the mRNA codons, and the ribosome links these amino acids into a polypeptide chain. This continues until a stop codon is reached, releasing the completed protein. (5 marks: 1 for transcription overview, 1 for mRNA processing, 1 for translation overview, 1 for tRNA/ribosome roles, 1 for stop codon/protein release)

13. Name the main components of a DNA molecule (3 marks).

    Deoxyribose sugar, phosphate group, nitrogenous bases (adenine, thymine, guanine, cytosine). (3 marks: 1 for sugar, 1 for phosphate, 1 for nitrogenous bases)

14. Compare and contrast the roles of mRNA, tRNA, and rRNA in protein synthesis (6 marks).

    mRNA (Messenger RNA): Carries genetic instructions from DNA to ribosomes. 2marks

    tRNA (Transfer RNA): Brings amino acids to the ribosome and pairs with mRNA codons using its anticodon.2marks

    rRNA (Ribosomal RNA): Forms part of the ribosome structure and helps in peptide bond formation. 2marks

15. Describe the Watson and Crick model of DNA (4 marks).

    DNA has a double helix structure, with two strands running in opposite directions (antiparallel).

    Each strand is made of nucleotides, consisting of a sugar, phosphate, and nitrogenous base.

Base pairing occurs through hydrogen bonds: adenine (A) pairs with thymine (T) and guanine (G) pairs with cytosine (C).

The two strands twist to form a right-handed spiral, stabilized by hydrogen bonding and base stacking.

APPENDIX E

Lesson Plan for the Study

Conventional Lesson Plan 1

Topic: Cell II

Subtopic: Nucleic Acids

Duration: 70 minutes

Specific Objectives

By the end of the lesson, students should be able to:

1. Define the term nucleic acid.
2. Distinguish between the various types of nucleic acids.
3. Explain the double helix structure of DNA.
4. Describe the structure features of RNA.
5. Summarise the stages involved in DNA replication.

Relevant Prior Knowledge

Students are already familiar with the main components and functions of cells, including the nucleus as the site where genetic material is stored.

Teaching and Learning Resources

Cardboard with an illustrated model of DNA and RNA.

Lesson Outline

Introduction (5 minutes):

Teacher Activity: The teacher reviews prior knowledge through questions, e.g., “Which part of the cell stores genetic material?”

Student Activity: Students respond, e.g., “Genetic material is found in the nucleus.”

Content Development (30 minutes):

Step 1: Nucleic Acids

The teacher facilitates brainstorming on the meaning and types of nucleic acids.

Students discuss and identify DNA and RNA.

Step 2: Structures of DNA and RNA

The teacher explains structural details using the cardboard model.

Students observe and contribute to the discussion.

Step 3: DNA Replication

The teacher explains the mechanism and enzyme involvement.

Students listen and participate in a guided discussion.

Key Concepts

1. Nucleic acids are large molecules made of nucleotides, located mainly in the nucleus.
2. DNA and RNA are the two major types of nucleic acids.
3. DNA consists of nucleotides (sugar, phosphate, nitrogenous bases). Bases: Purines (A, G), Pyrimidines (C, T). Double helix: complementary pairing (A-T, C-G).
4. RNA is single-stranded; Uracil replaces Thymine. Types: mRNA, tRNA, rRNA.
5. DNA replication involves strand unwinding (helicase), base pairing, and strand completion by polymerase and ligase.

Application (20 minutes):

Teacher: Asks: ‘‘Which DNA helix would be harder to separate: one rich in A-T or one rich in G-C pairs? Why?”

Students: Respond, applying knowledge of hydrogen bonding.

Closure (15 minutes):

The teacher summarises the main ideas and evaluates with review questions.

Students respond and clarify misconceptions.

Assignment:

1. Draw and label a DNA structure of five nucleotides.
2. State three differences between DNA and RNA.
3. Outline the stages of DNA replication.

Computer Simulation Lesson Plan 1

Topic: Cell II

Subtopic: Nucleic Acids

Duration: 70 minutes

Specific Objectives

By the end of the lesson, students should be able to:

1. Provide a definition of nucleic acids.
2. Distinguish between the major types of nucleic acids.
3. Use a simulation to investigate the DNA double helix.
4. Examine the structure of RNA.
5. Illustrate the replication of DNA using a computer-based model.

Relevant Prior Knowledge

Students know the structure and functions of cells and the nucleus as the storage site of genetic material.

Teaching and Learning Resources

Simulation software, projector, and computer laboratory.

Lesson Outline

Introduction (5minutes):

Teacher Activity: Reviews prior knowledge, e.g., "Where is genetic material located in the cell?"

Student Activity*:* Responds, e.g., "In the nucleus."

Content Development (30 minutes):

Step 1: Nucleic Acids

The teacher introduces the concept through a short animation in the software.

Students watch and identify DNA and RNA.

Step 2: DNA and RNA Structures

Teacher guides interactive simulation; students manipulate models of DNA and RNA.

Students explore base pairing and molecular components.

Step 3: DNA Replication

The teacher demonstrates replication with the simulation, highlighting helicase, polymerase, and ligase.

Students predict next steps and answer embedded quiz questions.

Key Concepts

1. Nucleic acids are nucleotide polymers located in the nucleus.
2. DNA has a double helix with complementary base pairing (A-T, C-G). RNA is single-stranded and uses Uracil.

3. DNA replication: strand separation, complementary pairing, and strand synthesis by enzymes.

Application (20 minutes):

Teacher: Simulation scenario: Compare the separation energy of A-T-rich vs. G-C-rich DNA.

Students: Manipulate the simulation and explain the results.

Closure (15 minutes):

Teacher summarises with key review questions via simulation, e.g., “What is the function of polymerase during replication?”

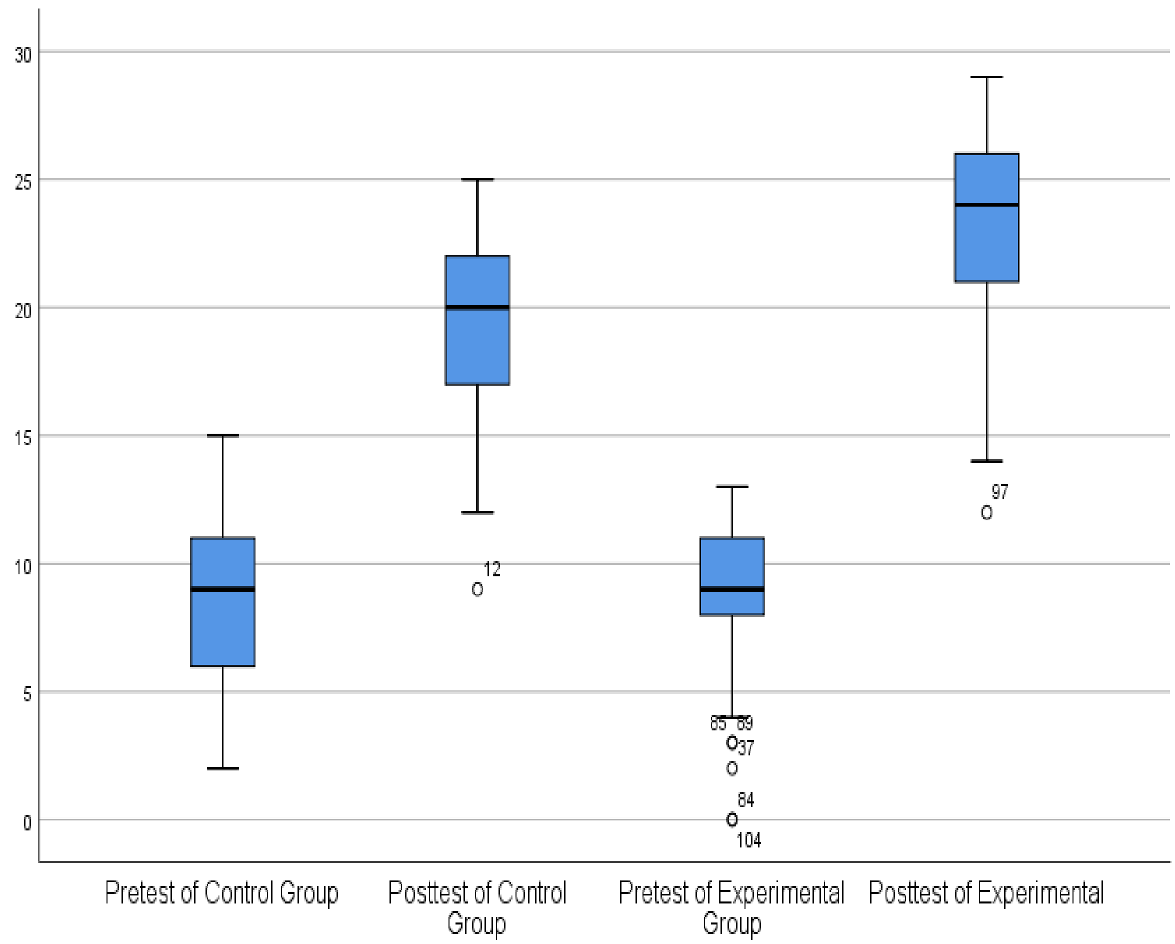
Students respond and consolidate learning.

Assignment:

1. Illustrate a DNA strand with five nucleotide units.
2. State three key structural differences between DNA and RNA.
3. List the stages of DNA duplication.

APPENDIX F

Box-plot of Normality Test



APPENDIX G

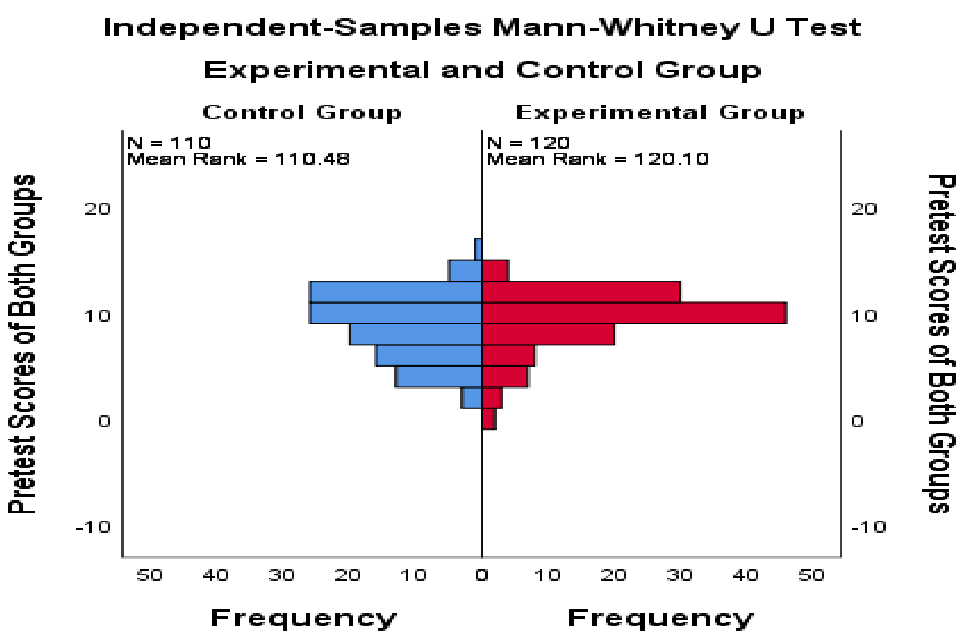
Independent Sample Mann-Whitney U test in respect to research question One

PRE-TEST RESULTS

Independent-Samples Mann-Whitney U Test

Summary

Total N	230
Mann-Whitney U	6047.500
Wilcoxon W	12152.500
Test Statistic	6047.500
Standard Error	500.700
Standardized Test Statistic	-1.103
Asymptotic Sig.(2-sided test)	.270

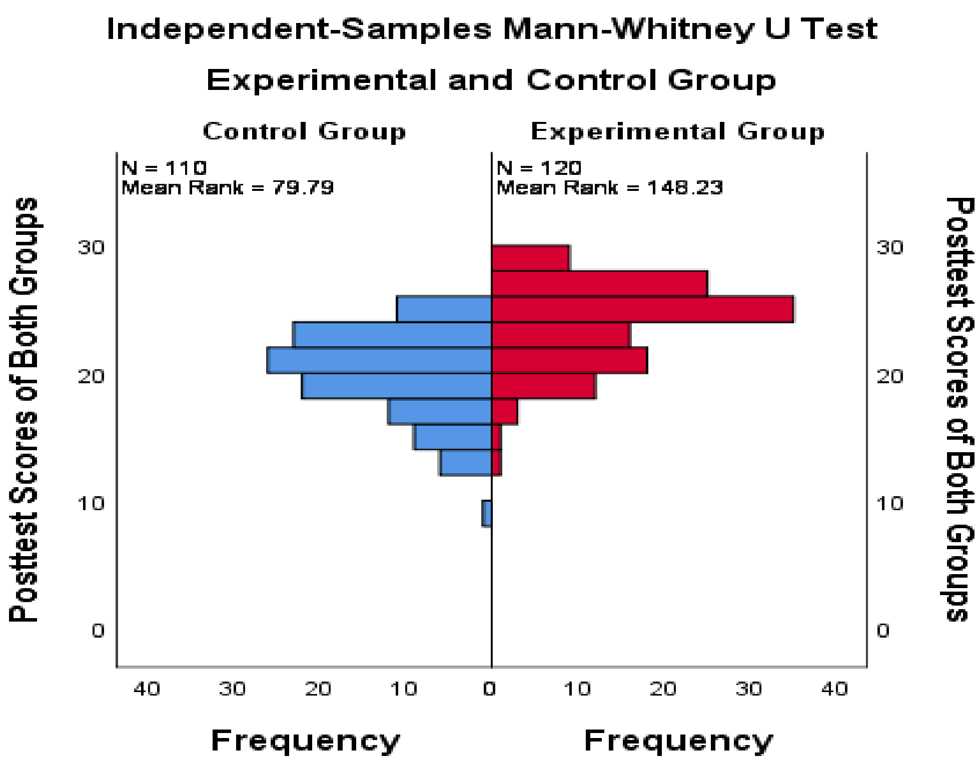


POST-TEST RESULTS

Independent-Samples Mann-Whitney U Test

Summary

Total N	230
Mann-Whitney U	2672.000
Wilcoxon W	8777.000
Test Statistic	2672.000
Standard Error	502.399
Standardized Test Statistic	-7.818
Asymptotic Sig.(2-sided test)	.000



APPENDIX H

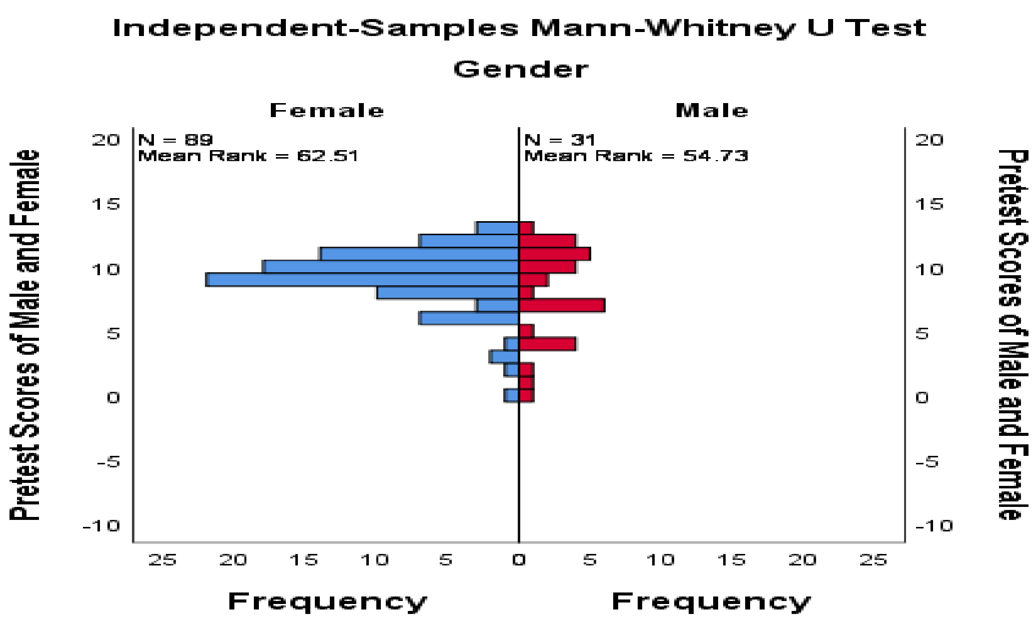
Independent Sample Mann-Whitney U test in respect to research question Two

PRE-TEST RESULTS

Independent-Samples Mann-Whitney U Test

Summary

Total N	120
Mann-Whitney U	1200.500
Wilcoxon W	1696.500
Test Statistic	1200.500
Standard Error	165.087
Standardized Test Statistic	-1.084
Asymptotic Sig.(2-sided test)	.278

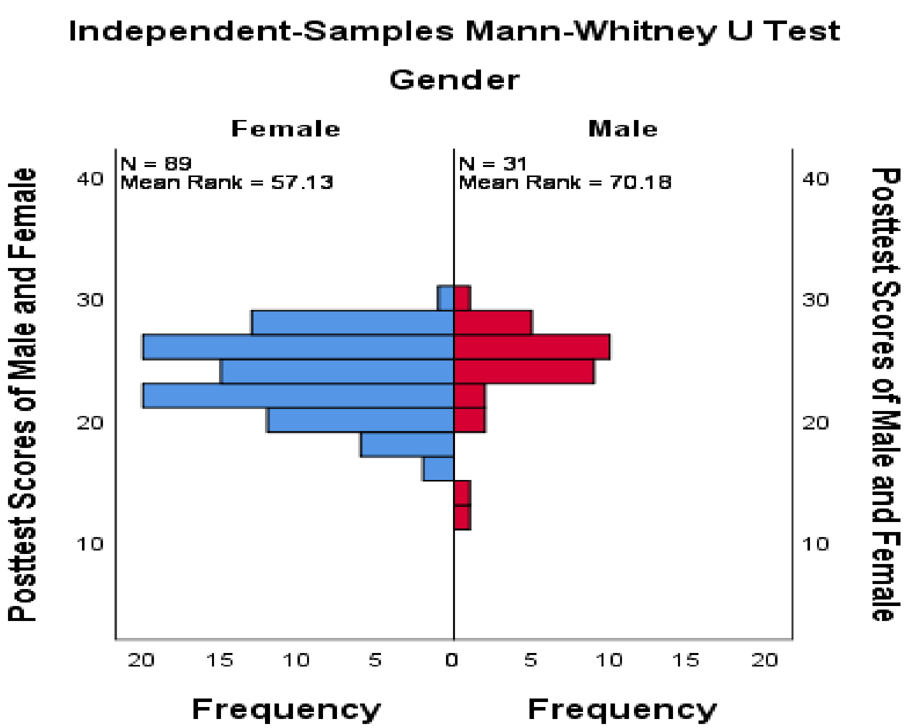


POST-TEST RESULTS

Independent-Samples Mann-Whitney U Test

Summary

Total N	120
Mann-Whitney U	1679.500
Wilcoxon W	2175.500
Test Statistic	1679.500
Standard Error	165.880
Standardized Test Statistic	1.809
Asymptotic Sig.(2-sided test)	.071



APPENDIX I

Paired Sample Wilcoxon Signed Rank test in respect to research question Three

Related-Samples Wilcoxon Signed Rank Test

Summary

Total N	120
Test Statistic	7260.000
Standard Error	381.440
Standardized Test Statistic	9.517
Asymptotic Sig.(2-sided test)	.000