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Visualizing the Invisible: The Impact of Computer Simulations on Student Attitude Towards Genetics Education

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Abstract: This study investigates senior high school students' attitudes toward the use of computer simulations in the teaching and learning of genetics in Ghana. Grounded in constructivist learning theory and technological integration frameworks, the research explores how interactive simulations particularly those from PhET Interactive Simulations enhance conceptual understanding, engagement, and motivation in genetics education. Employing a mixed-method descriptive survey design, data were collected from 104 SHS Biology students through questionnaires and focus group interviews. Principal Component Analysis revealed four dominant attitudinal dimensions: positive and proactive, analytic and experiential, enthusiastic and visual, practical and engaging. Quantitative findings indicated a high overall mean score (M = 3.71, SD = 0.073), reflecting strong student agreement with the benefits of simulation-based instruction. Qualitative insights further affirmed students' enthusiasm, citing improved comprehension, visual clarity, and increased interest in genetics. Teachers also reported reduced instructional burden and enhanced student performance. The study concludes that computer simulations are a powerful pedagogical tool capable of transforming genetics education in resource-constrained contexts, provided infrastructural and training barriers are addressed.

Keywords: Academic Performance, Attitude, Computer Simulation, Genetics, Student views.
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Introduction

Technological advancement is contributing immensely to educational development in the 21st century. In view of Ouahi *et al.* (2022), technology in education enable learners control their own learning process, as well as offer them ready access to a vast amount of information over which the teacher has no control. Tebabal & Kahssay (2011) see these benefits, as the reasons why most educational systems are adapting to the changes brought about by today's technological advancement. While most educational systems across the world are changing and modernizing the content of learning, technological adaptation may not be successful unless the teaching models are based on information resources.

Teaching models do not only offer practical education; they also enhance understanding. Computer Aided Instructional programs (CAIP) is one of the teaching models based on the use of information system resources. Computer-Aided Instructional Programs are software designed to facilitate and enhance learning experiences through computer-based instruction. They include educational tools, including simulations, interactive tutorials, quizzes, and multimedia presentations. Among the CAIP, Murugesan observed that computer simulations provide dynamic and interactive environments that allow users to explore concepts, practice skills, and experiment with various scenarios (Murugesan, 2019). These simulations help imitate real-world phenomena or abstract concepts, providing learners with a hands-on, experiential learning experience that complements traditional instructional methods. Therefore, simulation is a representation or model of an event, object, or some phenomenon. Akpan and Andre (1999) used computer simulation to model dynamic systems of objects in a real or imagined world in science education. These computer simulations gave students the opportunity to observe a real-world experience and interact with it. According to Strauss and Kinzie (1994), simulations are most useful for modelling labs that are impractical, expensive, impossible, or too dangerous to run. Simulations are useful in many other ways, including contributing to conceptual change (Stieff, 2003); providing open-ended experiences for students (Kevogo *et al.,* 2013) and problem-solving experiences (Murugesan, 2019).

In the 21st Century, especially in advance countries, computer simulations have become more significant tool than other educational materials such as text books, novels, film and television, radio programs and podcasts in the classroom. Its popularity is partly due to the fact that simulations are quite easy to introduce especially in today's curriculum. Many educators are using simulations for its efficiency. Again, in the field of genetics, computer simulations have revolutionized the teaching and learning of genetics by offering dynamic, interactive platforms that engage students in hands-on exploration (Rutten *et al.,* 2012). These simulations provide a visual representation of complex genetic concepts to students, allowing them to manipulate variables, observe outcomes, and gain a deeper understanding of genetic principles. In view of Gruner (2012), simulating genetic processes such as Mendelian inheritance, genetic recombination, and population genetics, can help students experiment with various scenarios, speeding up their comprehension and retention of genetic concepts.

Since computer simulations provide visual and interactive representations of complex biological processes, they have become significant tool in teaching genetics in recent years. Most studies recognize simulation as an effective strategy for enhancing students' understanding as well as igniting students interests in exploration and experimentation (Dziubaniuk *et al.,* 2023). Despite this potential, many biology teachers in Ghana still prefer traditional teaching methods to the adoption of simulation technologies. In view of Ouahi *et al.* (2021) this attitude can be attributed to a lack of training, limited access to technological resources, and insufficient pedagogical support

According to *Dziubaniuk et al.* (2023), most students exhibit positive attitude to the employment of computer simulations in the classroom. The interactive and visual nature of simulations are well appreciated as students benefit from the clarity of complex genetic concepts and processes. Researchers have observed that simulations present learners with many advantages, including the exploration and experiment with different scenarios, making learning more engaging and enjoyable, and appreciating the hands-on approach to learning (Morris, 2020). according to Howden (2012), some students' express enthusiasm for the ability to manipulate variables and observe the effects on genetic outcomes, which deepens their understanding of genetic principles. They also value the opportunity to work at their own pace and repeat simulations as needed, which helps to reinforce their learning (Howden, 2012). Due to the numerous contests saddled with the traditional methods of instruction and learning genetics in Senior high schools, and the potential benefits to be derived from the use of simulation-based instruction, it is crucial to explore how computer simulations can enhance students' attitude in genetics in Ghanaian senior high schools. Therefore, this research seeks to unearth students' attitude of computer simulations on the teaching and learning of genetics in senior high schools.

Purpose of the Study

The purpose of this study was to assess the attitude of students towards the use of computer simulation on the teaching and learning of genetics in senior high schools.

Research Question of the Study

What is the attitude of students towards the use of computer simulations to teach genetics?

Literature Review

Conceptual Framework

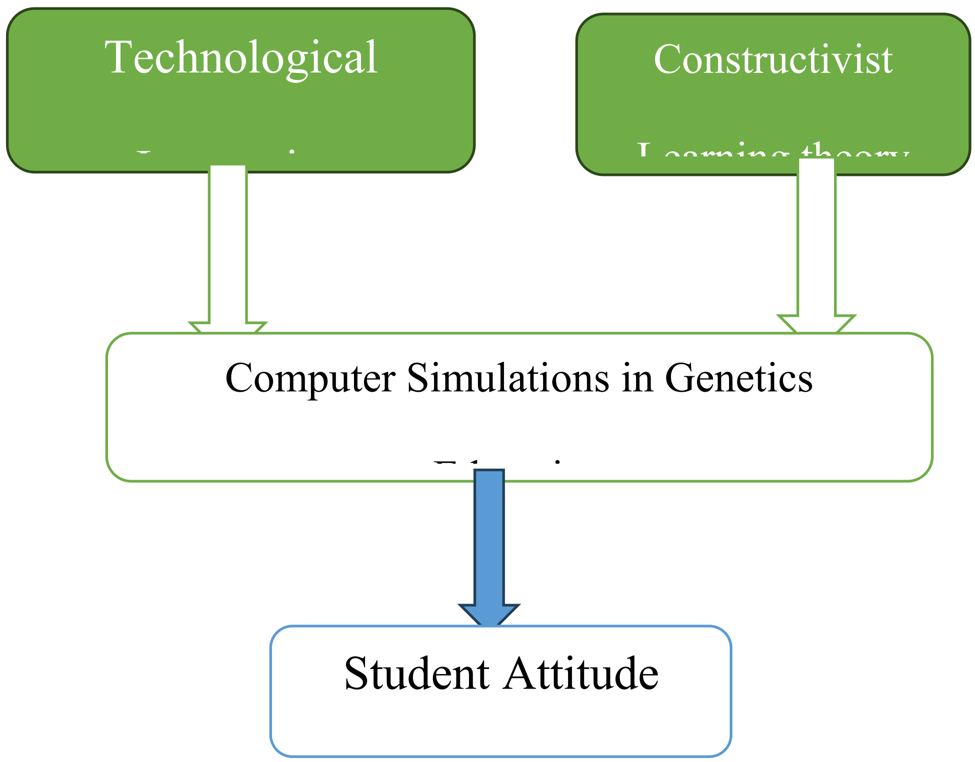
This study is grounded in constructivist learning theory and technological integration frameworks, which together emphasize that learners actively construct knowledge through interactive engagement with learning tools. Computer simulations exemplify these principles by providing dynamic, visual, and exploratory environments that enable students to manipulate variables, test hypotheses, and visualize abstract genetic processes such as Mendelian inheritance, DNA replication, and gene expression. Through these interactions, learners bridge the gap between theoretical and experiential understanding. According to constructivist theorists, meaningful learning occurs when students are actively involved in constructing their own understanding rather than passively receiving information (Stieff & Wilensky, 2003). Simulations operationalize this by creating inquiry-based, self-paced learning opportunities that foster autonomy, reflection, and problem-solving (Rutten et al., 2012; Dziubaniuk et al., 2023).

Integrating technology into education, particularly through simulation tools, further enhances cognitive engagement and motivation by linking visual perception to conceptual comprehension. When learners interact with realistic virtual models, they internalize complex biological phenomena more effectively and develop positive attitudes toward learning science (Morris, 2020; Ouahi et al., 2022). However, the successful application of simulation-based instruction depends on contextual factors such as teacher competency, infrastructural availability, and institutional support, which influence students' experiences and dispositions (Kevogo et al., 2013; Ouahi et al., 2021).

Consequently, this framework positions student attitude as a mediating variable between simulation-based instruction and learning outcomes in genetics education. Students' perceptions of usefulness, enjoyment, and engagement determine how effectively simulations improve understanding and retention. The framework therefore assumes that when simulation technologies are pedagogically aligned and well-supported, they enhance student attitudes, foster deeper comprehension, and lead to improved academic achievement in genetics.

Figure 1

Conceptual Framework of the Study.



This framework therefore situates student attitude as a pivotal variable mediating the effectiveness of simulation-based instruction. Attitude encompasses students’ perceptions of usefulness, engagement, and satisfaction with simulations, which in turn influence their willingness to participate and persist in learning activities. By examining these attitudinal dimensions, the study aims to illuminate the potential of simulations to transform genetics education in resource-constrained contexts.

Concept of Computer Simulations

Computer simulation, a computer model, or a computational model is a computer program, run on a single computer, or a network of computers, that attempts to simulate an abstract model of a particular system. Computer simulation refers to a computer crossing point' creates a heightened sense of presence, allowing users to feel immersed in the simulated environment (Hong, J. Y, 2010). Research by Zacharia and Anderson (2003) shows that computer simulations enhance students' ability to articulate and apply what they've learned. Computer simulations are powerful tools used across various fields to model complex systems and phenomena.

At its core, a computer simulation is a digital representation of a real-world process or system, created and manipulated through algorithms and mathematical models. These simulations enable students, researchers, engineers, scientists, and decision-makers to explore, analyze, and understand the behavior of systems in a controlled virtual environment (Sifuna, 2016). Computer simulations have become an integral tool in mathematical modeling across various natural systems, including physics (computational physics), astrophysics, chemistry, and biology, as well as human systems in fields like economics, psychology, social science, and engineering (Egara *et al.,* 2022). Running a system's model is what constitutes simulation.

This approach enables exploration and discovery of new technologies, as well as performance estimation for systems that are too complex to solve analytically. Computer simulations can range from brief, minute-long programs to extensive, hour-long network-based simulations, and even prolonged simulations that run for days. The scope of events simulated by computers has surpassed what's feasible with traditional mathematical modeling methods. (Ouahi *et al.,* 2022). One key aspect of computer simulations is their ability to mimic real-world scenarios with a high degree of accuracy. By inputting relevant data and parameters into the simulation software, users can replicate the behavior of intricate systems, ranging from physical phenomena like weather patterns and fluid dynamics to socio-economic processes such as market behavior and population dynamics (Smetana & Bell, 2012). Through iterative refinement and validation against empirical data, simulations can become increasingly reliable representations of reality.

Another crucial feature of computer simulations is their versatility and scalability. Simulations can range from simple models running on a single computer to complex, multi-scale simulations distributed across high-performance computing clusters. This scalability allows researchers to tackle problems of varying complexity, from exploring fundamental scientific principles to optimizing industrial processes and designing advanced technologies (Rutten *et al.,* 2012).

Furthermore, computer simulations offer a safe and cost-effective means of experimentation. Instead of conducting expensive and potentially hazardous real-world experiments, researchers can simulate scenarios virtually, manipulating variables and observing outcomes without risk (Mengistu & Kahsay 2015). This aspect is particularly valuable in fields like medicine, where simulations can aid in drug development and treatment optimization without endangering patients. Additionally, simulations facilitate hypothesis testing and scenario analysis by allowing users to explore "what-if" scenarios and assess the consequences of different decisions or interventions (Nkemakolam *et al.,* 2018). This capability is invaluable in fields such as disaster management, where simulations can help predict the outcomes of various response strategies and mitigate potential risks. Moreover, computer simulations play a crucial role in education and training, providing students and professionals with interactive learning environments to explore theoretical concepts and gain practical experience (Kumar & Kumar, 2017). Simulations can simulate complex systems and processes in a way that is engaging and easily comprehensible, fostering deeper understanding and skill development (Kara- Zorluoglu et. al, 2025).

The Teaching and Learning of Genetic

Teaching genetics typically begins with foundational concepts such as Mendelian genetics, which explores the basic principles of inheritance through traits governed by single genes. Students learn about dominant and recessive alleles, Punnett squares, and inheritance patterns such as autosomal and sex-linked traits (Sugumar, 2024). This foundational knowledge serves as the building blocks for understanding more complex genetic phenomena. As students' progress, they delve into molecular genetics, which focuses on the structure and function of genes at the molecular level. This includes DNA replication, transcription, translation, and regulation of gene expression. Understanding these processes is crucial for grasping how genetic information is encoded, transmitted, and expressed in living organisms.

Additionally, modern genetics education incorporates the study of genomics, which involves analyzing entire genomes to understand the organization, function, and evolution of genes within an organism or population (Akwee *et al.,* 2012). With advancements in technology such as next-generation sequencing, students have the opportunity to explore genome-wide analyses and their implications for fields like personalized medicine, agriculture, and conservation biology. Teaching and learning genetics also involve practical laboratory experiences where students gain hands-on skills in techniques such as PCR (polymerase chain reaction), gel electrophoresis, DNA sequencing, and genetic engineering. These laboratory exercises not only reinforce theoretical concepts but also foster critical thinking, problem-solving, and experimental design skills essential for scientific inquiry. Furthermore, the ethical, social, and legal implications of genetics are integrated into the curriculum to encourage discussions on topics such as genetic testing, gene editing, genetic discrimination, and biotechnology regulation (Koomson *et al.,* 2020). By examining these issues, students develop a deeper understanding of the broader societal impacts of genetic research and applications. Overall, teaching and learning genetics encompass a diverse array of topics ranging from classical Mendelian genetics to cutting-edge genomic technologies and ethical considerations (Kiboss *et al.,* 2004). By engaging students in a multifaceted approach that combines theoretical knowledge with practical experimentation and critical thinking, educators can cultivate a deep understanding of genetics and its implications for society.

The Role of Computer Simulations in Teaching Genetic and Student Attitudes

Genetics, being the foundational concept in biology, is often a problematic area to teach since the ideas themselves are recondite and the phenomena take place at the molecular and even sub-molecular level. However, conventional forms of class and tutorial instruction can lack the effectiveness to convey the full measure of genetic action. This gap has seen the incorporation of computer simulations, as a useful tool in the portrayal of these genetics concepts as dynamic and realistic (Lavin *et al.,* 2021). Modern technologies in genetics education include computer-simulated genetics from some simple moving images to some complex three dimensional and virtual laboratories. That is why such tools let a student control variable, manage processes, and evaluate results that would be unfeasible to model in a classroom environment. For example, workflow can stunningly illustrate DNA replication, gene expression, and population genetics dynamically making it easier for students to grasp concepts that may otherwise seem abstract (Tibell & Harms, 2017).

Thus, using computer simulations in genetics education has numerous advantages; among them is encouraging active learning. It is convenient to work with components and not lose time on the sequence, allowing students to develop unique strategies, even practicing genetic phenomena solely (Collins, 2018). This interactivity is particularly helpful when it comes to understanding more information on issues like Mendelian inheritance, gene mutation, and gene control. According to de Jamil *et al.* (2018) such a form of learning fosters understanding, and higher-order thinking skills acquisition on the part of the learners, they make use of theories learned to solve real-life problems. Computer simulations also have the opportunity to provide an individual approach for learners where everybody can choose the type of learning he or she needs. Since most of these learning modules can be in large portions, these programs are flexible since they can suit students of different knowledge levels (Bernarducci, 2017). Since information and communications technology (ICT) based learning is not proscriptive, learners can move forward gradually; revisit or review the content, and/or re-simulate processes that may have been difficult the first time around. This adaptability makes simulations particularly good for students with different learning needs, which different students may have (Makransky *et al.,* 2016). Additionally, computer simulation relieves several drawbacks of conventional lab experiences including time limitations, availability of materials, equipment, or safety issues. While virtual learning in modern genetics curricula applies the best of both worlds, these real inherent limitations of apprenticeship traditions became the original learning impediments that virtual learning erases (Makransky *et al.,* 2019).

Additionally, to determine the usefulness of simulations as instructional aids in genetics it is also critical to look at the tendencies of students towards computer simulations. There are the following factors: first, students' readiness to use technology in learning environments; second, perceived advantages for comprehending genetic ideas. Observing the levels of engagement that traditional forms exercise and the simulation techniques applied can determine how these affect learning. Also, the perspectives of students regarding the realism and relevance of the genetical processes modeled within the frames of simulations as well as potential disadvantages or shortcomings contribute to the understanding of the role of the simulations in the learning process. Knowledge of these factors can be useful in designing the implementation of simulations into genetics teaching and learning.

Thus, the assessment of these components allows the recognition of the pattern of how computer simulations influence the learning achievements of students in genetics. This information can be used to further improve the approaches to teaching, adjust and build better simulations, and improve the overall quality of genetic education.

Assessing Student Attitudes Toward Computer Simulations in Genetics Education

This study identifies students' attitudes toward computer simulations as an important factor in effectively implementing computer simulations in teaching genetics. These attitudes play a huge role in participation, motivation, and learning. According to Rutten et al. (2012), students approach computer simulations in natural sciences, including genetics, with positive attitudes. Industry experience, student status, prior use, perceptions of interactivity and realism, and confidence in the program contribute to positive attitudes toward computer simulations in genetics education. Although it can be normal to be worried that the utilization of hi-tech, kinetic, and elaborate models surpasses ordinary approaches in capturing trainee attention and enhancing knowledge that remains in their long-term memory, based on the research findings by Smetana and Bell (2012).

Using simulations that enable the student to role-play the genetic processes and proportions, there is enhanced understanding and acquisition of knowledge as postulated by Levy, (2013). Hence, performing simulations at the student's own pace and with self-controlled activities increases their confidence resulting from repetitive practice (Lin & Suh, 2021). Also, like Computer-aided Process Simulations, it offers students an opportunity to practice in a virtual setting because of which the actual problem can be solved without major concerns (Makransky *et al.,* 2016). Nevertheless, it is necessary to realize that students' attitudes are conditioned by certain factors, such as interest in the material to be learned, prior experience with technologies, etc, and the approach to the use of simulations (Makransky *et al.,* 2019). The findings of the study are in line with those of Nsabayezu *et al.* (2022) who found that using computers in the teaching and learning process facilitates students to understand scientific phenomena since they visualize complex concepts. In addition, the integration of ICSs in teaching and learning science subjects particularly chemistry improves students' cognitive and affective domains. de Hoop *et al.* (2024) conclude that it's the right decision to integrate technology in the education system since students acquire a diverse set of skills that respond to the nation's need to achieve developmental goals.

Students' attitudes towards these lessons were understood to be the attitude of students towards chemistry. Compared to conventional instruction, which is teacher-centred and uses the lecture method, research on the effects of some novel instructional approaches on students' attitudes towards chemistry has produced inconclusive results (Chan & Bauer, 2015). Khaled *et al.* (2014) proposed incorporating computer simulations into classroom instruction to enhance students' attitudes toward physics, which in turn improves their performance. Similarly, Sarı *et al.* (2017) discovered that interactive computer simulations in scientific inquiry yield more positive attitudes toward physics compared to traditional teaching methods

Khaled *et al.* (2014) study shows that computer simulations substantially influence students' attitudes and perceptions of physics. Aşıksoy and İşlek (2017) found that computer simulation lab experiences have a positive effect on students' physics attitudes. Çetin's (2018) research revealed that cooperative simulation-based learning has a significantly greater impact on students' physics attitudes compared to traditional methods. Additionally, Kattayat *et al.* (2016) discovered a strong correlation between students' physics achievement and their attitude toward the subject when simulation-based training is used. Furthermore, Sari *et al.* (2019) discovered that computer-based labs and virtual applications enhanced students' attitudes. The use of Computer Simulations (CSs) enables students to conduct virtual experiments, manipulating variables to observe different outcomes (Widiyatmoko, 2018).

These virtual experiments allow students to model real-world systems, exploring various inputs, processes, and outputs, which is beneficial in science education. Consequently, simulations have significant potential to spark students' curiosity, foster creativity, and develop critical thinking skills, and encourage them to learn by doing. They allow students to experience and interact with natural events, challenge them, and provoke reactions. Consequently, simulations can customize learning to fit each student's needs, pace, interests, and abilities within an interactive virtual environment. Additionally, research has shown that simulations positively affect students' interest and attitude toward science (Sari *et al.,* 2019; Kattayat *et al.,* 2016). Notably, Sari et al. (2019) discovered that virtual applications and computer-based labs have a positive impact on students' attitudes and motivation.

Further research showed that technology in labs enhances student learning and attitudes (Oymak & Ogan-Bekiroglu, 2017). Bozkurt and Ilik (2010) found that simulations boosted students' physics achievement and beliefs. Kattayat *et al.* (2016) noted that simulation-based instruction in the classroom fosters more positive attitudes toward physics among students, leading to improved academic performance in the subject.

Further, the antecedents of students' perceptual attitudes have been identified as computation literacy, perceived usefulness, integration within the curriculum, perceived support of the instructor as well as perceived quality of the simulation used in genetics education. There is usually a more positive attitude toward computer-based learning tools exhibited by students who have higher computer literacy (Eksail & Afari, 2020). Prospective learners who feel that simulations will help improve academic performance in genetics and understanding are also more supportive of simulations. Instructional simulations that have been integrated into the course learning goals are likely to be more embraced by students than simulations that are randomly incorporated into a course (Rutten *et al.,* 2012).

Teacher interest and support have an impact on students' use of simulation; teachers showing interest and supporting the students increase their confidence level and real-life positive attitudes towards the use of simulations. Realistic and easy-to-navigate simulations of genetic processes tend to have more positive effects on attitudes (Lanjekar *et al.,* 2021) and negative effects with inaccurate and poorly designed simulations (Villena-Taranilla *et al.,* 2022).

These factors should be taken into consideration when measuring student attitudes toward computer simulations in genetics education. Questionnaires, interviews, or focus groups could be developed to measure students' attitudes towards or perceptions about the utility of simulations in the learning environment, their perception of how simulations improve their knowledge of genetics, easiness, navigability of the simulations, compatibility of the simulations to their genetics curriculum, the support their instructors provide in the use of the simulations, and their level of satisfaction when using the computer simulations.

In this way, the mentioned aspects, are to be comprehensively evaluated to increase the educators' and researchers' understanding of students' attitudes regarding the use of computer simulations in genetics content. This information may help to refine the approaches used in simulation development and application strategies regarding genetics education, as well as general learning methods, which eventually will contribute to the development of educational programs and raise student achievements.

Methods

The research employed for this study was the mixed-method descriptive survey design which combines both quantitative and qualitative methods to provide a more comprehensive understanding of a phenomenon. In this study, questionnaires were used to collect quantitative data on attitudes, or opinions students, while interviews were employed to gather qualitative data that provide deeper insights and explanations into participants' views and experiences (Pallant 2011). The sample size for this study comprised 104 SHS 3 Biology students from selected randomly from the participating schools.

Reliability of the Instrument

The questionnaire was piloted on 15 biology students. The study used the pilot test data to check for the reliability of the questionnaire, using Cronbach's Alpha test which.

Table 1
Reliability of the Research Questionnaire

Cronbach's Alpha	**N of Items**
.826	15

As represented in Table 1, the Cronbach Alpha value, which measured the internal consistency of the questionnaire items was 0.826. This value, according to Pallant (2011) indicates a preferable internal consistency of the questionnaire. This means that the internal consistency of the questionnaires was reliable.

Data Collection Procedure

Intervention

The intervention in this study was the use of computer simulation for teaching and learning genetic. Computer simulations are valuable tools for teaching genetics in schools, providing students with interactive and engaging experiences that help them understand complex genetic concepts (Barberousse et al., 2009). In this study, Biology Simulations from PhET Interactive Simulations was used. The PhET Interactive Simulations offer various biology simulations that cover genetics topics suitable for senior high school (SHS) students. The topics covered include interactive activities on Mendelian inheritance, Punnett squares, DNA replication, transcription, translation, and genetic mutations. Studies (Najib, Md-Ali, & Adams, 2010) have shown that Biology Simulations from PhET Interactive Simulations is effective for teaching genetics; hence its deployment in this current study.

The intervention phase spanned four weeks, comprising eight 80-minute instructional sessions (two lessons per week). Each session targeted specific genetics concepts aligned with the Ghana Education Service (GES) Senior High School Biology syllabus. The selected topics were:

1. Mendelian inheritance
2. Punnett squares and probability of inheritance
3. Structure and replication of DNA
4. Transcription and translation
5. Genetic mutations
6. Chromosomal behaviour during mitosis and meiosis

The lessons were conducted in computer laboratories equipped with laptops and projectors. Students were organized into small groups of 4–5 members, each sharing one computer to promote collaboration and discussion. Every session followed a three-phase learning cycle adapted from the Engage–Explore–Explain model:

- Engage: The teacher introduced the topic with a short discussion or question to activate prior knowledge (about 10 minutes).
- Explore: Students interacted directly with the PhET simulations (40–45 minutes). During this phase, they manipulated variables (e.g., allele combinations, mutation rates, or cell cycle stages) to observe genetic outcomes. The teacher acted as a facilitator, guiding inquiry and encouraging critical observation.
- Explain: In the final stage (20–25 minutes), students discussed their findings in groups and shared explanations with the class. The teacher clarified misconceptions, reinforced key principles, and linked the virtual experiences to real-world genetics applications.

After the intervention, students completed a 15-item attitude questionnaire, followed by focus group interviews with 12 randomly selected participants (six males and six females) to gain qualitative insights. Teachers were also interviewed to validate student perspectives and reflect on instructional experiences.

The entire teaching and data collection process lasted approximately five weeks, including orientation, intervention, and post-test phases. This structured approach ensured that both quantitative and qualitative data were obtained systematically to provide a comprehensive understanding of students' attitudes toward simulation-based learning. To illustrate the intervention process, Figures 1 to 5 present screenshots of the PhET Interactive Simulations used during the teaching sessions. These visuals depict the main genetics concepts explored including the structure and replication of DNA (Figures 1 and 2), cell division processes such as mitosis and meiosis (Figures 3 and 4), and Mendel's law of segregation (Figure 5). Each simulation served as an interactive learning environment where students could manipulate genetic variables and visualize molecular interactions in real time.

Simulation Screenshots

Figure 1

PhET Simulation Interface Showing DNA Structure.

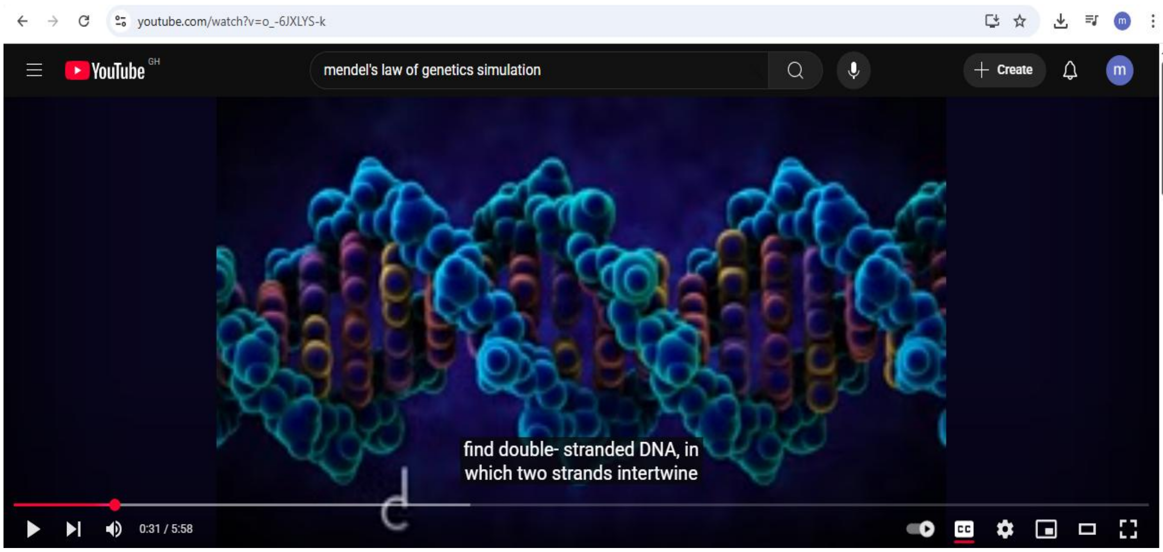


Figure 2

PhET Simulation Interface showing Replication of DNA

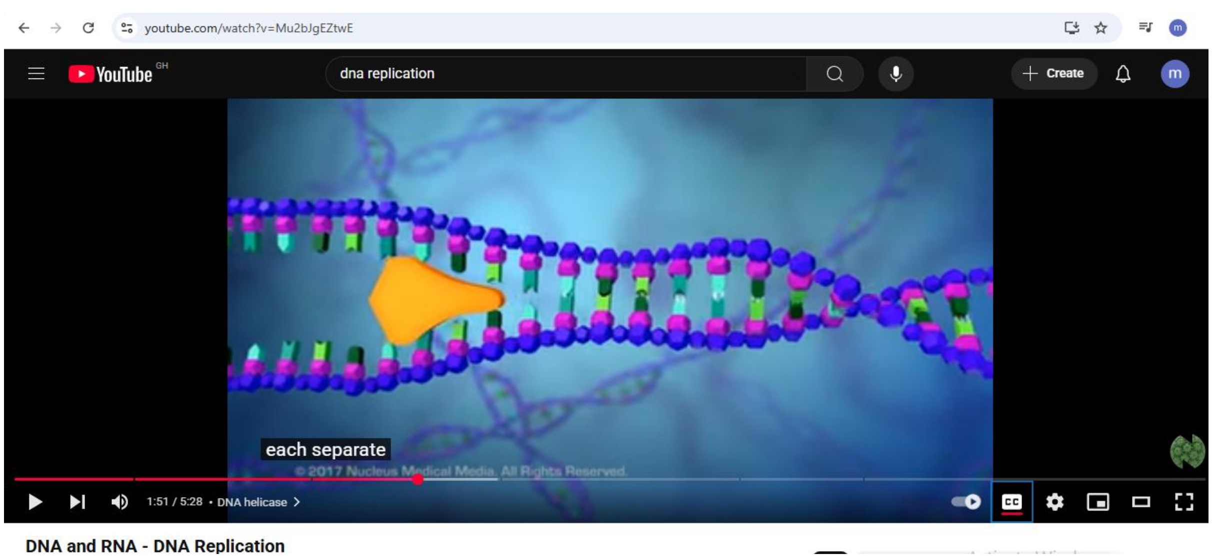


Figure 3

PhET Simulation Interface showing mitosis formation

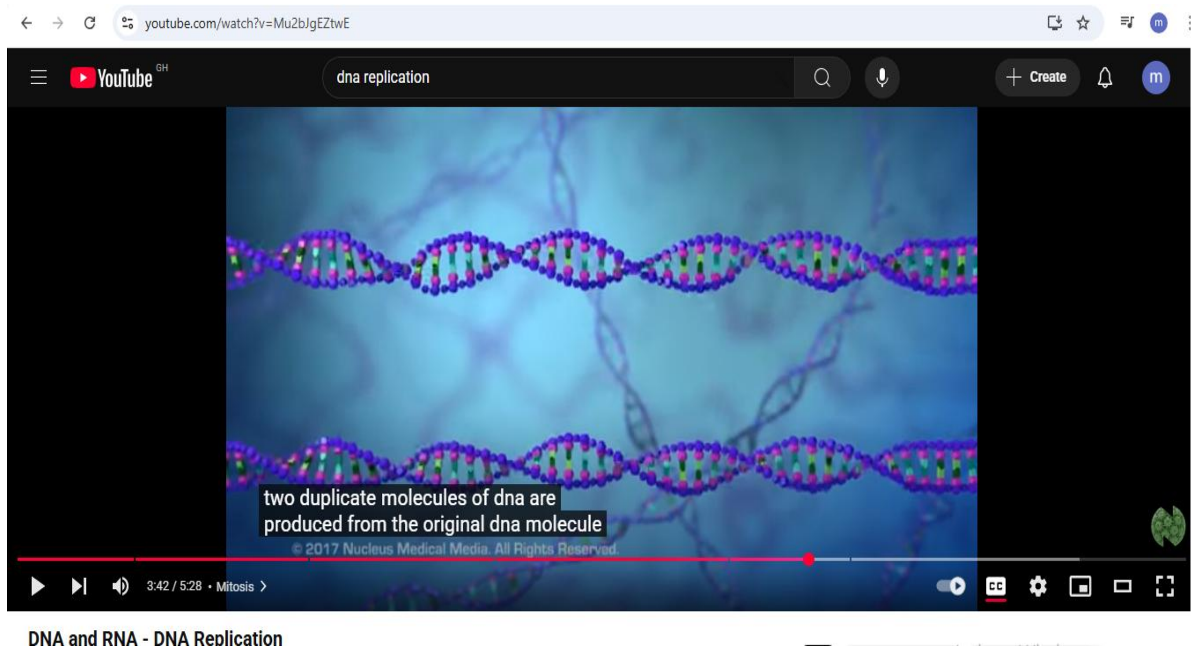


Figure 4

PhET Simulation Interface showing Meiosis formation

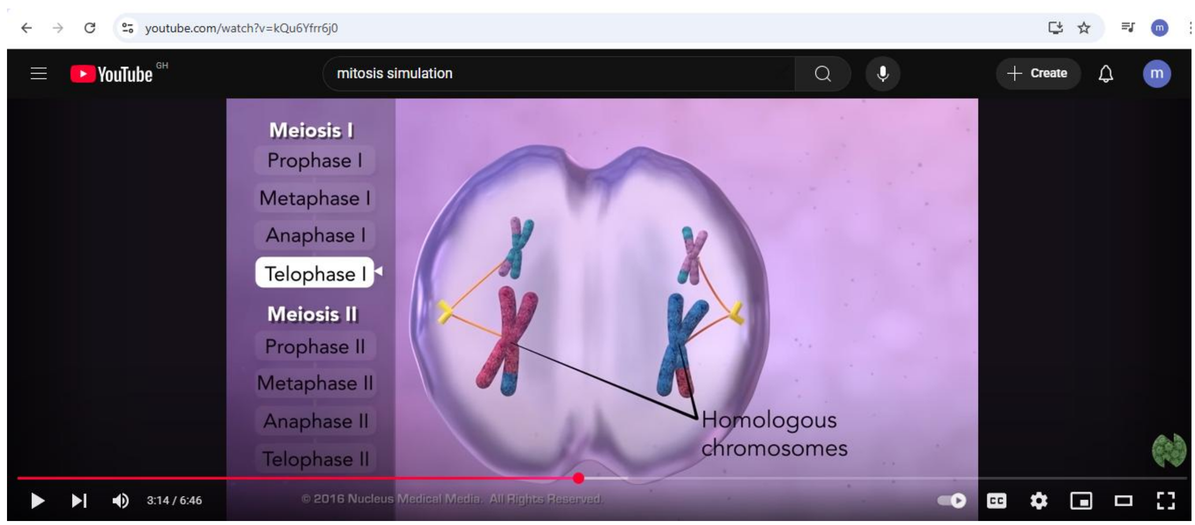
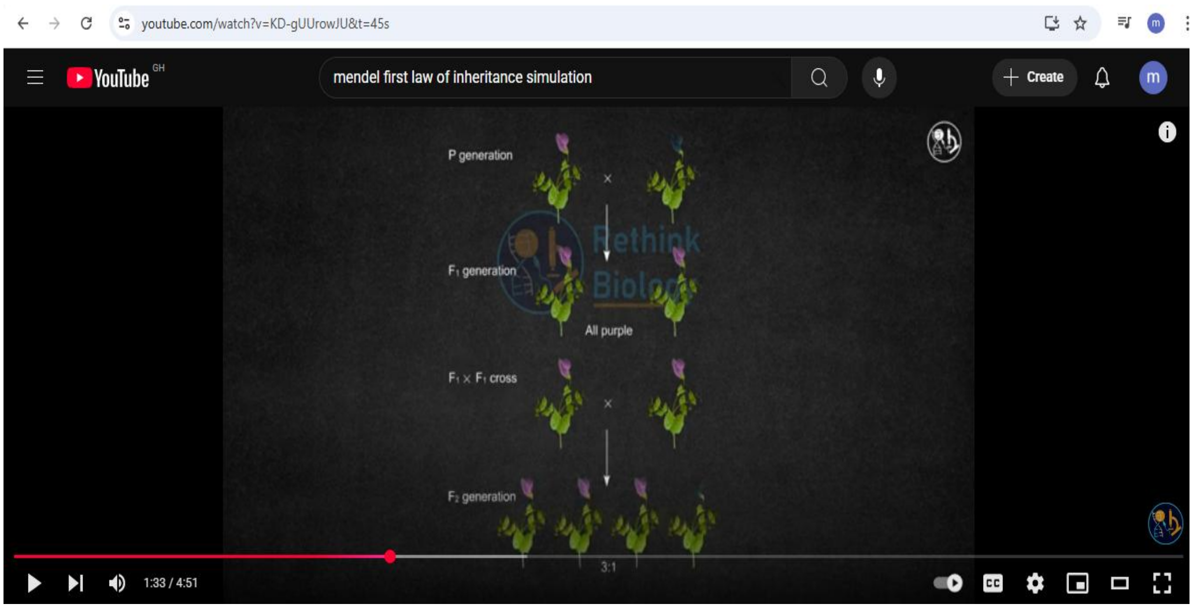


Figure 5

PhET Simulation Interface of Mendel's Law of Segregation



Post-Intervention Stage

Following the intervention phase, a questionnaire was administered, and students and students responded to it and also a focus group interview was done to know students views on the use of computer simulations.

Results

What is the attitude of students towards the use of computer simulations to teach genetics?

Table 2 outlines the results from the Principal Component Analysis (PCA), revealing four key components of students' attitudes, *Positive and Proactive, Analytic and Experiential, Enthusiastic and Visual, and Practical and Engaging*. These components highlight students' multidimensional appreciation for simulation-based learning.

Table 2

Components of Attitude of Student on the use of computer simulation

	Statements	Component 1	2	3	4
Positive and Proactive	The use of interactive simulation makes it simple and easier for me to study genetics	.885			
	Using interactions simulation instead of traditional methods does not scare me.	.875			
	I like interactive simulations because they can help me learn on my own at home with my computer	.861			
	Lessons become more interesting when interactive simulations are used..	.719			
Analytic and experiential	The simulations were highly effective due to its engaging features like clear visuals and graphics		.857		
	Simulations were beneficial because it allowed us to conduct experiments and observe them realistically		.819		
	I understood the content of genetics better with the help of the interactive simulations.		.805		
Enthusiastic and visual	The simulations' colourful and dynamic design made it useful for learning			.859	
	The simulation is helpful because it allows you to visualize the experiment.			.827	
Practical and engaging	The use of interactive simulation makes it simple and easier for me to study genetics.				.894
	I found the simulations we used were appealing.				.858
	With interactive simulations I can finish my homework faster				.816
	Students get interest in genetics when interactive simulations are used in teaching.				.664

Source: Field Data (2024)

Table 3

Total Variance Explained

	Initial Eigenvalues			**Extraction Sums of Squared Loadings**			**Rotation Sums of Squared Loadings**
Comp	**Total**	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**	**Total**
1	4.357	33.516	33.516	4.357	33.516	33.516	3.611
2	2.254	17.341	50.856	2.254	17.341	50.856	2.593
3	1.646	12.658	63.515	1.646	12.658	63.515	1.685
4	1.037	7.976	71.491	1.037	7.976	71.491	3.057
5	.774	5.958	77.449				
6	.534	4.106	81.555				
7	.521	4.011	85.566				
8	.450	3.462	89.028				
9	.404	3.106	92.134				
10	.376	2.889	95.023				
11	.289	2.226	97.249				
12	.204	1.571	98.820				
13	.153	1.180	100.000				

As shown in Table 3, the extracted components account for a cumulative 71.49% of the total variance, confirming the adequacy of the four-factor model. The first component alone explains 33.52% of the total variance, followed by 17.34%, 12.66%, and 7.98% for the subsequent components.

The Eigenvalues presented in Table 3 indicate that there are four categories or components of attitudes towards computer simulations. The first component explains 33.5% of attitude of students towards computer simulation, the second component explains 17.3% and third component 12.6% and the fourth component explains 7.9% of attitude towards computer simulation. The study assessed the attitudes of students by first decomposing the attitude items into components using Principal Component Analysis (PCA). The PCA results shows the Total Variance Explained in Table 4 above.

Table 4

Attitude Towards the Use of Simulations in Teaching Genetics

Categories	Statements	N	Mean	Std. Dev
Positive and Proactive	The use of interactive simulation makes it simple and easier for me to study genetics	104	3.76	.704
	I am not afraid to use simulation instead of traditional methods.	104	3.65	.747
	I like interactive simulations because they can help me learn on my own at home with my computer.	104	3.72	.717
	Lessons become more interesting when interactive simulations are used.	104	3.41	.732
Analytic and experiential	The simulations were highly effective due to its engaging features like clear visuals and graphics	104	3.85	.553
	Simulations were beneficial because it allowed us to conduct experiments and observe them realistically.	104	3.62	.612
	I understood the content of genetics better with the help of the interactive simulations	104	3.48	.638
Enthusiastic and visual	The simulations' colourful and dynamic design made it useful for learning	104	3.83	.492
	The simulations were helpful because they allowed me to visualize the experiments.	104	3.85	.553
Practical and engaging	Using interactive simulation makes it easier for me to study genetics	104	3.76	.661
	I found the simulations we used very appealing	104	3.76	.661
	With interactive simulations I can finish my homework faster	104	3.74	.668
	Students get interest in genetics when interactive simulations are used in teaching.	104	3.86	.645
	OVERALL,		**3.71**	**0.073**

Source: Field Data (2024)

Table 4 presents the descriptive statistics for each attitudinal component. The overall mean score indicates strong positive attitudes toward simulation-based instruction. According to Sullivan and Artino (2013), mean values above

3.5 reflect agreement, confirming that most students found the simulations beneficial, engaging, and effective in facilitating understanding of genetics concepts.

The overall mean score for students' attitudes toward the use of computer simulations in teaching genetics is 3.71 with a standard deviation of 0.073. According to the Likert scale interpretation by Sullivan and Artino (2013), a weighted average in the range of 3.50 to 4.49 indicates an agreement with the statements, reflecting a positive attitude. This suggests that students generally perceive the use of computer simulations as beneficial and engaging in the context of learning genetics. The relatively low standard deviation also indicates that there was a high level of agreement among respondents, with responses showing little variability. This consistency implies that most students share similar positive perceptions of simulation tools, likely due to the interactive, visual, and practical learning support these tools provide. Therefore, it can be concluded that students hold a positive disposition toward the integration of computer simulations in genetics instruction, recognizing its value in enhancing comprehension and stimulating interest in the subject.

Qualitative Analysis on Attitude of Students Towards the Use of Simulation

Participants from the schools were included in the study to ascertain their attitude towards the use of simulation in teaching genetics. The responses given by the participants were positive as the students in School A exhibited enthusiasm towards the use of simulation in their learning routine. One participant indicated that;

> *"The software is remarkable and it makes it easier to understand the concept of genetics. I have gotten a visual representation of how genes change and I do not think that I will ever forget such a phenomenon" (Student Participant 1).*

Another participant stated that he is able to study better when simulations are used in class and that the interactive nature of the simulations makes the lessons more interesting. He stated emphatically that;

> *"The software is in fact a significant advantage in ensuring that we the students understand what is being taught in the classroom. I think that if we are to use simulation in every lesson, our performance will sky rocket because it is very difficult to forget illustrations made in the simulation as compared to if the traditional method of teaching was used." (Student Participant 2).*

The teachers also exhibited enthusiasm in using the simulation software to teach as they indicated that teaching certain abstract concepts such as genetics can be very challenging for students to understand. However, the use of computer simulation has really simplified the concept of genetics making it easier for students to understand and making the teachers' workload quite lesser for them too. Teachers do not have to stress so much as the software is able to break down concepts from the bare minimum upwards until students understand the concept entirely. One teacher participant revealed that;

> *"The simulation software has made this lesson a success and I think I like the feedback. When I compare the feedback, I had during the use of the traditional method of teaching to the feedback I had after the simulation software was used to teach, you could see a significant*

difference in the performance of the students. I am very happy because the students were in smiles and nodding in affirmation to what was being taught, making the lesson interesting and easier for me too (Teacher Participant 1).

Another participant indicated emphatically that;

"You know it is very rare to have this software in the current educational system of this country due to the lack of ICT infrastructure. This software if it were to be available in each and every senior high school in the country, I do not think that we would have been discussing poor performance of the students when they write their external exams. This simulation software is really helpful………

In fact, what I really like about the simulation software is that the graphics used in the software helps the students to visualize experiment made in the software. Its colourful nature makes it much exciting to use. The students themselves are able to interact with the simulation software and helps them observe them as if they were actually real. I am really impressed about the software and its influence on performance of the students." (Teacher Participant 2).

Qualitative Findings: Student and Teacher Perspectives

A thematic synthesis of student focus-group responses and teacher interviews revealed four interrelated themes that mirrored the PCA-derived dimensions identified in the quantitative results *Enthusiastic & Visual, Positive & Proactive, Analytic & Experiential, and Practical & Engaging*. Students consistently expressed that the computer simulations "made abstract ideas visible," enabling them to observe allele combinations, DNA processes, and cell-division stages as they unfolded step-by-step. This visualisation enhanced conceptual clarity, reduced cognitive load, and supported the development of more accurate mental models of genetic mechanisms. Teachers confirmed that traditionally challenging topics such as gene expression and meiotic segregation elicited fewer misconceptions when taught through animated, interactive simulations. Learners also highlighted the value of self-paced exploration and the ability to manipulate variables without fear of making mistakes, describing a sense of control that enhanced both confidence and persistence. Many students reported revisiting simulations outside classroom hours "to check" or "try again," demonstrating growing autonomy and motivation toward self-directed learning.

Students further perceived the simulations as "experiments we could actually run," appreciating how parameter changes such as mutation rate or genotype ratios produced immediate, interpretable outcomes that fostered inquiry and evidence-based reasoning. Teachers observed that simulation-based lessons prompted more thoughtful questioning, peer discussion, and precise use of scientific language, reflecting deeper engagement with the subject matter. Learners described the interfaces as "appealing" and "easy to follow," noting that revision tasks were completed more efficiently because they could replay and verify processes at their own pace. Teachers added that simulations reduced logistical burdens associated with laboratory lessons while maintaining high levels of student focus and participation.

Despite these advantages, participants identified certain implementation constraints, including limited access to devices and internet connectivity, time constraints within the school timetable, and varying levels of ICT proficiency among students. Teachers emphasized the importance of brief pre-lesson orientations and structured inquiry prompts to guide exploration, especially for learners unfamiliar with digital tools.

Integration with Quantitative Results

The qualitative insights strongly complement the quantitative findings. Students' descriptions of enhanced visual understanding and hands-on experimentation reinforce the Enthusiastic & Visual and Analytic & Experiential dimensions revealed by the PCA. Their accounts of autonomy, motivation, and confidence align with the Positive & Proactive component, while observations related to appeal and task efficiency correspond to the Practical & Engaging factor. Collectively, these perspectives explain the high overall attitude scores: computer simulations not only lowered representational barriers but also increased learner control, curiosity, and satisfaction making genetics both comprehensible and enjoyable to study.

Discussions

The findings of the study are in line with those of Nsabayezu *et al.* (2022) who found that using computers in the teaching and learning process facilitates students to understand scientific phenomena since they visualize complex concepts. In addition, the integration of ICSs in teaching and learning science subjects particularly chemistry improves students' cognitive and affective domains. de Hoop *et al.* (2024) conclude that it's the right decision to integrate technology in the education system since students acquire a diverse set of skills that respond to the nation's need to achieve developmental goals. Students' attitudes towards these lessons were understood to be the attitude of students towards chemistry. Compared to conventional instruction, which is teacher-centred and uses the lecture method, research on the effects of some novel instructional approaches on students' attitudes towards chemistry has produced inconclusive results (Chan & Bauer, 2015). Kattayat *et al.* (2016) proposed incorporating computer simulations into classroom instruction to enhance students' attitudes toward physics, which in turn improves their performance. Similarly, Sarı *et al.* (2017) discovered that interactive computer simulations in scientific inquiry yield more positive attitudes toward physics compared to traditional teaching methods.

Abou Faour and Ayoubi's (2017) study shows that computer simulations substantially influence students' attitudes and perceptions of physics. Aşıksoy and İşlek (2017) found that computer simulation lab experiences have a positive effect on students' physics attitudes. Çetin's (2018) research revealed that cooperative simulation-based learning has a significantly greater impact on students' physics attitudes compared to traditional methods. Additionally, Kattayat *et al.* (2016) discovered a strong correlation between students' physics achievement and their attitude toward the subject when simulation-based training is used.

Furthermore, Sari *et al.* (2019) discovered that computer-based labs and virtual applications enhanced students' attitudes. The use of Computer Simulations (CSs) enables students to conduct virtual experiments, manipulating variables to observe different outcomes (Widiyatmoko, 2018). These virtual experiments allow students to model real-world systems, exploring various inputs, processes, and outputs, which is beneficial in science education. Consequently, simulations have significant potential to spark students' curiosity, foster creativity, and develop critical thinking skills, and encourage them to learn by doing. They allow students to experience and interact with natural events, challenge them, and provoke reactions (Council, 2011). Consequently, simulations can customize learning to fit each student's needs, pace, interests, and abilities within an interactive virtual environment. Additionally, research has shown that simulations positively affect students' interest and attitude toward science (Sari *et al.,* 2019; Kattayat *et al.,* 2016). Notably, Sari *et al.* (2019) discovered that virtual applications and computer-based labs have a positive impact on students' attitudes and motivation.

Further research showed that technology in labs enhances student learning and attitudes (Oymak & Ogan-Bekiroglu, 2017). Bozkurt and Ilik (2010) found that simulations boosted students' physics achievement and beliefs. Kattayat *et al.* (2016) noted that simulation-based instruction in the classroom fosters more positive attitudes toward physics among students, leading to improved academic performance in the subject.

Conclusion

This study provides compelling evidence that computer simulations significantly enhance students' attitudes toward the teaching and learning of genetics in Ghanaian senior high schools. The integration of interactive simulations particularly those offering visual, dynamic, and self-paced learning experiences was met with overwhelmingly positive responses from both students and teachers. Quantitative analysis revealed strong agreement across multiple attitudinal dimensions, including enthusiasm, engagement, and perceived effectiveness, while qualitative insights underscored the transformative impact of simulations on comprehension and classroom dynamics. The findings affirm the pedagogical value of simulation-based instruction in demystifying abstract genetic concepts and fostering learner autonomy. However, the study also highlights systemic barriers such as limited ICT infrastructure and insufficient teacher training, which must be addressed to scale the benefits of simulation technologies across educational contexts. By recognizing student attitudes as a critical mediator of instructional success, this research advocates for strategic investments in digital tools, professional development, and curriculum alignment to promote equitable and effective science education. Ultimately, the study underscores that when thoughtfully implemented, computer simulations are not merely technological enhancements they are catalysts for deeper understanding, sustained interest, and improved academic outcomes in genetics education.

Practical Implications of the Study

- The positive student attitudes toward simulations suggest that genetics curricula should integrate simulation-based modules to complement traditional instruction.

- Simulations can be used to visualize abstract genetic processes like DNA replication, Mendelian inheritance, and gene expression, making them more accessible to diverse learners.
- The study highlights the need for targeted training programs to equip biology teachers with the skills to effectively implement and facilitate simulation-based instruction.
- Workshops and continuous professional development should focus on pedagogical strategies for using simulations, troubleshooting technical issues, and aligning simulations with learning outcomes.
- Ministries and education boards can use these findings to justify funding proposals, pilot programs, and partnerships with edtech providers.

Limitations and Future Directions

While the study provides convergent evidence that simulations support positive attitudes toward learning genetics, several limitations temper the inferences and point to concrete next steps:

1. The implementation period was relatively brief, which limits claims about durability of attitudinal shifts and the development of stable study practices. Future work should adopt longer, multi-unit implementations and include delayed post-tests to assess retention of both attitudes and understanding.
2. Because simulations were new to many students, positive responses may reflect novelty or social desirability. Longer exposures, counter-balanced designs, and comparison groups (e.g., simulation-plus vs. high-quality non-simulation visualisations) can help separate genuine pedagogical value from novelty.
3. Participants were drawn from a limited number of schools, which may cap generalizability across regions with different ICT access profiles. Future research should employ multi-site sampling with school-level covariates (device ratio, connectivity, teacher ICT experience) to test for contextual moderation.
4. Although teachers facilitated exploration and debriefs, the study did not formally measure instructional fidelity (e.g., time-on-task in phases, adherence to inquiry prompts). Incorporating short fidelity checklists and teacher logs would clarify which enactment features drive outcomes.
5. Variability in prior ICT fluency likely influenced students' comfort and pace. Brief skills warm-ups, accessible help cards, and peer-support structures can help equalise access; analyses stratified by prior ICT readiness would make equity impacts visible.
6. Focus-group size and available time limited the number of voices per school. Future work should expand the corpus of interviews, use member-checking for theme validation, and report inter-coder agreement to bolster qualitative trustworthiness.

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