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Impact of Physics Education Technology (Phet) Interactive Simulations and Hands-On Laboratory Experiments on Senior High School Students' Academic Performance in Genetics in Ghana

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ABSTRACT

This study examined how the integration of Physics Education Technology (PhET) interactive simulations and hands-on laboratory experiments influenced the academic performance of students in selected genetics topics at Bonzo Kaku Senior High School in Ghana's Ellembelle District. Concerns over persistent misconceptions, declining achievement, and low student motivation in genetics led to the adoption of a pragmatic action research design grounded in Kolb's Experiential Learning Theory. The research used a convergent parallel mixed-methods framework, gathering both quantitative and qualitative data from a purposively selected group of 212 third-year students. Teaching interventions incorporating PhET simulations and practical laboratory work were designed to address key genetics concepts, including gene expression, inheritance patterns, and chromosomal behavior. Academic performance was measured through pre- and post-tests, student perceptions were gathered via questionnaires, and in-depth qualitative insights were obtained through interviews. Quantitative analysis employed the Wilcoxon rank test, Mann-Whitney U test, Two-Way ANOVA, and descriptive statistics, while qualitative data were interpreted through thematic analysis. Findings revealed that students harbored considerable misconceptions about genetics: of the 20 multiple-choice questions administered, only three were answered correctly without any misconceptions. The study also identified the highly abstract nature of genetics instruction as a key driver of these misunderstandings, underscoring the need for the PhET and laboratory-based interventions that followed. The instructional intervention yielded substantial gains in both genetics performance and laboratory competencies, with scores rising by 46% and 50%, respectively. Notably, female students outperformed their male counterparts by 12% in genetics and by 10% in laboratory skills following the intervention. The study further found that PhET simulations had a more pronounced positive effect on the genetics performance of female students compared to males, though no gender-based differences emerged in the development of laboratory skills. Beyond measurable academic outcomes, the intervention cultivated greater student engagement, stronger critical thinking abilities, and a heightened interest in science. The study concludes that combining PhET simulations with hands-on laboratory activities represents a highly effective instructional strategy for teaching abstract and complex scientific content. It advocates for curriculum reform, targeted professional development for educators, and broader access to both digital tools and laboratory facilities. In doing so, the study makes a meaningful contribution to the

advancement of STEM education in Ghana through an evidence-based, student-centered approach that promotes both academic excellence and scientific literacy.

Keywords: Biology, Genetics, Genes, Heredity, Genetic variation, PhET Interactive Simulation, Biology Laboratory Experiment, Academic performance, Conceptual understanding in genetics

INTRODUCTION

Over the past fifteen years, technological advancements have substantially influenced multiple domains of human activity, including education. The incorporation of emerging technologies into pedagogical practice has improved access to learning resources and enhanced students' learning outcomes across diverse educational contexts globally. In particular, simulation-based and other interactive digital tools enable learners to develop a more profound understanding of scientific concepts while accommodating individual learning preferences, thereby supporting more personalised forms of instruction (Sadler et al., 2016). Furthermore, such technologies have been shown to stimulate interest in STEM (science, technology, engineering, and mathematics) disciplines and may contribute to increased student aspirations toward STEM-related careers.

Sadler et al. (2016) conducted a study involving 311 middle school students from Ohio, Pennsylvania, West Virginia, and New York to examine the impact of simulation-based learning on students' scientific inquiry skills and attitudes toward science. The intervention, implemented through The Challenger Learning Center, engaged students in a two-hour immersive simulation in which they collaborated in teams to address challenges associated with a category three hurricane and a volcanic eruption. Analysis of pre- and post-intervention surveys and assessments indicated improvements in several domains, particularly students' perceptions of scientists and scientific work. However, the study also identified gender-based differences, with male students demonstrating greater interest in scientific careers and a more pronounced shift toward positive scientific attitudes compared to female students (Sadler et al., 2016). Differences in content achievement across classrooms were further attributed to variations in teachers' preparatory instruction prior to the simulation.

Beyond cognitive gains, student engagement and motivation are widely recognised as critical determinants of success in science education. Learners who are both motivated and actively engaged are more likely to persist in the face of academic challenges and to achieve higher levels of performance. One effective strategy for fostering engagement is the contextualisation of curriculum content within real-life experiences and socially relevant contexts. In this regard, socio-scientific issues (SSIs): complex, real-world problems that integrate scientific and societal dimensions; offer meaningful opportunities for active learning by enabling students to connect classroom science with everyday life (Sadler et al., 2016).

Instruction based on socio-scientific issues typically centres on socially relevant themes, promotes higher-order cognitive processes, and requires learners to integrate both scientific knowledge and social considerations. This pedagogical approach encourages evidence-based reasoning and the evaluation of multiple perspectives when addressing authentic problems. Within this framework, proximal assessments are employed during instruction to inform immediate pedagogical adjustments based on learner performance, whereas distal assessments, such as end-of-unit examinations, are used to evaluate overall learning outcomes after instruction has been completed.

In one study, 69 secondary students in Florida participated in a three-week socio-scientific issue-based curriculum focusing on biotechnology and sexually transmitted diseases. Students explored the emergence of a new viral strain, its impact on communities, and the role of biotechnology in identifying the disease-causing agent. Proximal and distal assessments indicated significant gains in student performance, underscoring the educational value of contextualising learning content within students' lived experiences (Sadler et al., 2016). These outcomes suggest that socio-scientific issue-based instruction not only enhances student engagement and academic achievement but also promotes civic engagement by fostering collaboration, evidence-based reasoning, and the effective use of relevant technologies in problem-solving contexts.

Engagement with real-world problems further contributes to learners' self-efficacy, equipping them with the confidence to approach both academic tasks and everyday challenges in a structured and rational manner. The study also highlights the pedagogical importance of employing both proximal and distal assessment strategies to monitor student learning progression. Such assessments serve a dual purpose: they determine whether learners have met predefined learning standards and simultaneously provide actionable feedback to guide instructional decision-making. In this regard, differentiated and personalised instruction remains essential, given that individual learners and classrooms exhibit diverse learning needs and trajectories.

As technological capabilities continue to evolve and their applications in education expand, there is an increasing imperative to integrate these tools systematically into classroom instruction across educational systems. Educational technology provides extensive opportunities to enhance instructional delivery, assessment practices, and lesson planning, particularly within science education, where abstract concepts often benefit from visualisation and interactivity. Sezer (2016) reports that students demonstrate higher levels of engagement when instructional technologies are used, especially when such tools are adaptable and cover a wide range of topics and learning domains.

One pedagogical approach that effectively utilises educational technology is the flipped classroom model. In this instructional design, learners are exposed to instructional content independently, typically outside the classroom, before engaging in structured classroom activities focused on discussion, application, and problem-solving. This model encourages learners to develop independent study habits and foundational understanding prior to class sessions, thereby enabling more meaningful peer interaction, collaborative learning, and deeper conceptual engagement during in-class activities.

Students learn differently due to factors such as culture, background, and prior knowledge, while teachers also vary in their teaching methods, depending on their background, style, and experience (Batuyong & Antonio, 2018; Khan et al., 2016). Effective teaching is essential for ensuring that all learners are meaningfully engaged and supported in achieving academic success. Within this context, classroom management, broadly defined as the range of strategies, behaviours, and instructional decisions employed by teachers within the classroom environment, serves a central function in promoting inquiry-based learning. Effective management practices establish a structured yet supportive learning environment in which students feel psychologically safe to participate, ask questions, and explore new ideas without fear of ridicule or embarrassment.

A study conducted by Antonio and Batuyong (2018) investigated the influence of different classroom management styles, namely interventionist, non-interventionist, and interactionist approaches, on classroom climate and student achievement. The findings revealed that the interactionist approach, which emphasises the dynamic interplay between students' choices and the classroom environment, produced the most favourable classroom climate for both teachers and learners.

Additionally, students in classrooms led by interactionist teachers achieved higher academic success compared to those in classrooms with interventionist or non-interventionist approaches. The traditional textbook-and-lecture approach is still common in many classrooms, but it often fails to engage all students, particularly in science education. Conversely, online education provides flexibility and access to vast amounts of information but has high incompletion rates, suggesting that it does not suit every learner (Stockwell et al., 2015). To combine the benefits of both methods, a blended learning approach, which mixes online and face-to-face learning, is gaining popularity.

A study conducted by Stockwell and colleagues (2015) examined the impact of pre-class video assignments combined with in-class problem-solving activities on student engagement, satisfaction, and academic performance. The findings indicated that students who engaged with video-based instructional materials prior to class were more likely to attend lessons and reported higher levels of satisfaction compared to those who relied primarily on textbook-based preparation.

Additionally, students who engaged in problem-solving activities scored higher on assessments than those who participated in traditional lectures (Bryne, 2020; Liu, 2014). These findings highlight the effectiveness of blending technology and interactive learning methods to improve student outcomes.

Overall, integrating technology into classrooms, combined with effective classroom management and engaging instructional strategies, can enhance student learning, motivation, and academic performance.

The findings indicate that students achieved higher levels of academic performance when instructors adopted a blended learning approach that integrated online or electronic resources with face-to-face problem-solving activities. This instructional strategy also led to greater student satisfaction and improved learning outcomes compared to traditional teaching methods (Stockwell et al., 2015).

Engaging middle school students in science poses challenges, particularly because the content often feels abstract and difficult to visualize, such as atomic structures, genes, or DNA. Teaching complex topics like electrostatics can be daunting since magnetic fields and charges are not easily manipulated in traditional settings. To address this, students benefit from constructing testable and flexible models, though this process can be difficult (Supurwoko et al., 2017). To engage students who may be less inclined toward science, teachers are increasingly incorporating virtual simulations and educational games into instruction. These tools scaffold learners' exploration of scientific concepts and support the development of deeper conceptual understanding by providing interactive and experiential learning opportunities.

Researchers investigated the impact of *Supercharged!*, a 3D computer simulation game developed to teach electrostatic concepts. The game enables students to navigate a spaceship through a series of obstacles by manipulating charge types and magnitudes, with the ship's motion determined by its interaction with electromagnetic fields. The study involved 91 eighth-grade students, divided into an experimental group that used the simulation and a control group that received traditional guided inquiry instruction. Pre- and post-assessment results indicated that students in the experimental group demonstrated modest but statistically significant gains in their understanding of electrostatics compared to those in the control group (Supurwoko et al., 2017). In addition, learners in the experimental condition produced more detailed and conceptually grounded explanations, frequently drawing on elements of the simulation, whereas students in the control group tended to rely more heavily on memorisation (Supurwoko et al., 2017).

The effectiveness of simulations is not limited to individual game-based applications. Platforms such as PhET, developed by the University of Colorado, provide learners with interactive opportunities to explore scientific phenomena that are often difficult or impossible to investigate within traditional laboratory settings. PhET simulations allow students to manipulate variables and receive immediate feedback, promoting inquiry-based learning with minimal instructor guidance. Research shows a growing interest in PhET, especially among high achieving students, though there are disparities in access, with lower interest among minorities and those below the poverty level (Zhang, 2014; Yuliah, et al., 2018).

PhET simulations are praised for supporting inquiry-based learning in ways that traditional labs cannot. They provide visual representations, controls, and feedback, all designed to guide student thinking. For instance, learners are able to interact with DNA or examine atomic structures, tasks that cannot be practically carried out in a conventional laboratory (Perkins et al., 2015). The authors propose a combined instructional approach in which virtual and physical laboratories are used together, with simulations first supporting the introduction and development of concepts, followed by hands-on experiments that allow students to apply and verify their understanding (Perkins et al., 2015).

A related study in Indonesia examined how PhET simulations could enhance scientific creativity through a collaborative creativity learning model. Junior high school students were assessed on scientific creativity, such as hypothesizing and problem-solving, before and after using a PhET simulation about mechanics. The simulation's phases—problem identification, idea exploration, collaboration, elaboration, and evaluation—led to significant improvements in students' creativity (Astutik & Prahani, 2018; Yunzal & Casinillo, 2020). Students also reported feeling more confident in their scientific creativity and found the learning process engaging and enjoyable. Ultimately, tools like PhET simulations and blended learning approaches not only foster deeper content understanding but also enhance engagement, creativity, and academic performance. As technology continues to evolve, integrating these resources into science education is vital for engaging students and supporting inquiry-based learning.

Laboratory experiments play a significant role in genetics by providing students with hands-on experiences to reinforce theoretical concepts and develop practical skills (Wilcox & Lewandowski, 2017). Through laboratory activities, students engage in scientific inquiry, data collection, and analysis, thereby deepening their understanding of genetic principles (Yunzal & Casinillo, 2020). Furthermore, laboratory experiments promote collaborative learning environments where students can apply theoretical knowledge to real-world scenarios (Russell et al., 2017). An essential component of science education, as emphasized by Bunterm et al. (2014), is the provision and effective utilisation of specialised equipment, laboratory facilities, and instructional resources. Well-equipped, properly designed, and safe school laboratories provide the foundation for meaningful practical exercises in science teaching and learning (Chamberlain, Lancaster, Parson, & Perkins, 2014). When adequate resources are accessible and utilized, learners are able to develop scientific reasoning rather than relying on rote memorization. This process not only enhances knowledge acquisition but also fosters enthusiasm for biology. Furthermore, resource accessibility encourages teachers to adopt learner-centered approaches in place of traditional teacher-centered methods, which are often less effective. Ngman-wara (2005) emphasized that practical activities allow students to learn through hands-on experience, critical thinking, and skill development in handling tools and equipment. They also promote attentiveness to instructions, accurate documentation of observations and results, data organization, and the ability to draw informed conclusions. Based on the importance of PhET simulation and laboratory experiments in improving students' academic performance, this study, therefore, utilises these two educational interventions concurrently to ascertain their impact on students' performance in genetics by evaluating the effectiveness of these technology-enhanced learning tools.

Objective of the study

The main objective of this study is to examine and assess the effects of incorporating Physics Education Technology (PhET) simulations alongside hands-on laboratory experiments in the teaching and learning of genetics concepts at Bonzo Kaku Senior High School in the Ellembelle District of the Western Region. Specifically, the study aims to;

1. assess the effectiveness of laboratory experiments in enhancing students' engagement and practical skills in genetics.
2. determine the effect of both PhET simulations and laboratory experiments on students' prior knowledge and understanding in enhancing students' academic performance.

Related literature

Theoretical Framework

The theoretical foundation of this study was Kolb's Experiential Learning Model (Kolb, 1984). Developed by David Kolb, this model conceptualises learning as a cyclical process comprising four stages: concrete experience, reflective observation, abstract conceptualisation, and active experimentation. It posits that effective learning occurs through continuous engagement in this cycle, where individuals actively experience, reflect on, conceptualise, and apply knowledge.

Kolb's model is widely regarded as an influential framework that emphasises the centrality of experience in the learning process. It is particularly relevant to laboratory-based instruction, where hands-on activities play a critical role in knowledge acquisition and skill development. The experiential learning cycle is illustrated in Figure 1):

1. **Concrete Experience**: This stage involves encountering a new experience or situation, which could be a novel encounter or a reinterpretation of existing experiences. Here, students engage in laboratory experiments where they observe genetic traits in organisms or use PhET simulations to explore genetic inheritance patterns.
2. **Reflective Observation**: Learners reflect on the new experience, focusing on any inconsistencies between their understanding and the experience itself. Students make reflective observation which involve students discussing their observations, identifying patterns, and relating them to genetic principles learned in class.
3. **Abstract Conceptualization**: Reflection leads to the development of new ideas or modifications to existing abstract concepts based on the learning experience. Students begin to understand the underlying principles and theories behind the concrete experiences. Abstract conceptualisation involves students formulating hypotheses, constructing genetic models, and applying theoretical frameworks to explain observed phenomena.
4. **Active Experimentation**: Newly formed or modified concepts are put into practice through experimentation, where learners apply their ideas in real-world scenarios to observe outcomes. Learners engage in active experimentation to test their hypotheses, validate theories, and further enhance their understanding. In genetics, active experimentation entails planning and carrying out experiments, interpreting data, and forming conclusions from the findings. According to Kolb's learning theory, this process aligns with four distinct learning styles derived from the four-stage learning cycle:
   - **Diverging (CE/RO)**: Individuals who prefer this style are imaginative, emotional, and excel at viewing situations from multiple perspectives.
   - **Assimilating (AC/RO)**: Learners with this style focus on abstract concepts and reflective observation, emphasising understanding and creating theoretical models.

- **Converging (AC/AE)**: Students with this style are practical and prefer applying concepts in real-world situations through active experimentation.
- **Accommodating (CE/AE)**: This learning style emphasises concrete experience and active experimentation, where individuals learn best by doing and engaging in hands-on activities.

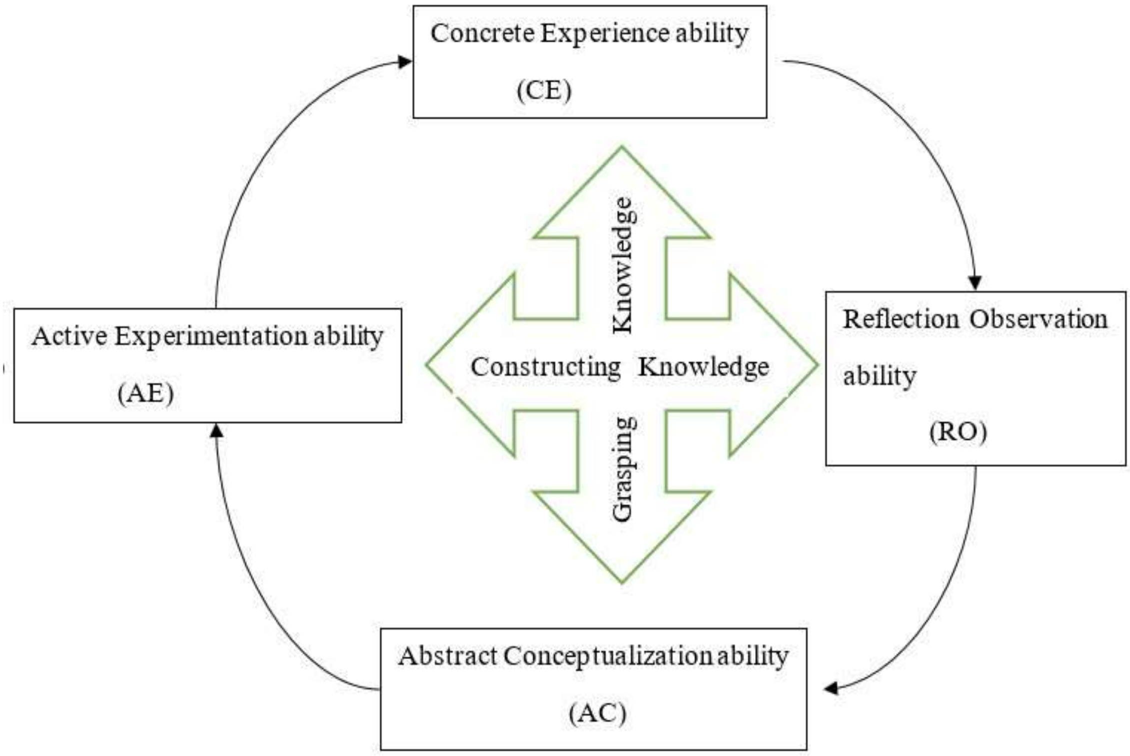

Figure1: Kolb's experiential learning model (Adopted from Kolb, 1984)

Understanding learners' preferred learning styles is important because it enables teachers to adapt instructional strategies to meet individual needs and improve the learning experience. Kolb's model emphasizes the interconnected nature of learning, highlighting that effective learning takes place when learners move through all four stages of the cycle.

Kolb's Experiential Learning Model provides a strong framework for examining the impact of PhET simulations and laboratory experiments in genetics education. The four stages of the model, which are concrete experience, reflective observation, abstract conceptualisation, and active experimentation, closely align with both virtual simulations and practical laboratory activities. PhET simulations support students in visualising abstract genetic concepts, while laboratory experiments reinforce theoretical knowledge through direct hands-on engagement. When combined, these approaches enhance conceptual understanding, promote critical thinking, build practical skills, and improve the ability to apply genetics knowledge in real-life situations.

Through the integration of laboratory activities and interactive simulations, students can engage in direct experiences, reflect on their observations, develop conceptual understanding, and test genetic principles in practice. This approach is consistent with Kolb's theory and provides a holistic learning experience that accommodates different learning styles and strengthens students' understanding and performance in genetics.

Kolb's Experiential Learning Model also draws attention to individual differences among learners and the importance of experience and reflection in learning. In laboratory-based science instruction, especially in genetics education supported by PhET simulations, the model helps create engaging learning environments that encourage critical thinking, problem-solving skills, and deeper comprehension of complex scientific ideas.

Conceptual Framework

The conceptual framework (Fig 2) for this analysis posits that both PhET simulations and laboratory experiments serve as independent variables that can impact various aspects of student learning, including performance, prior knowledge, engagement, understanding, and interest. The framework hypothesizes that the use of PhET simulations and laboratory experiments will positively influence these dependent variables through their unique affordances and instructional benefits.

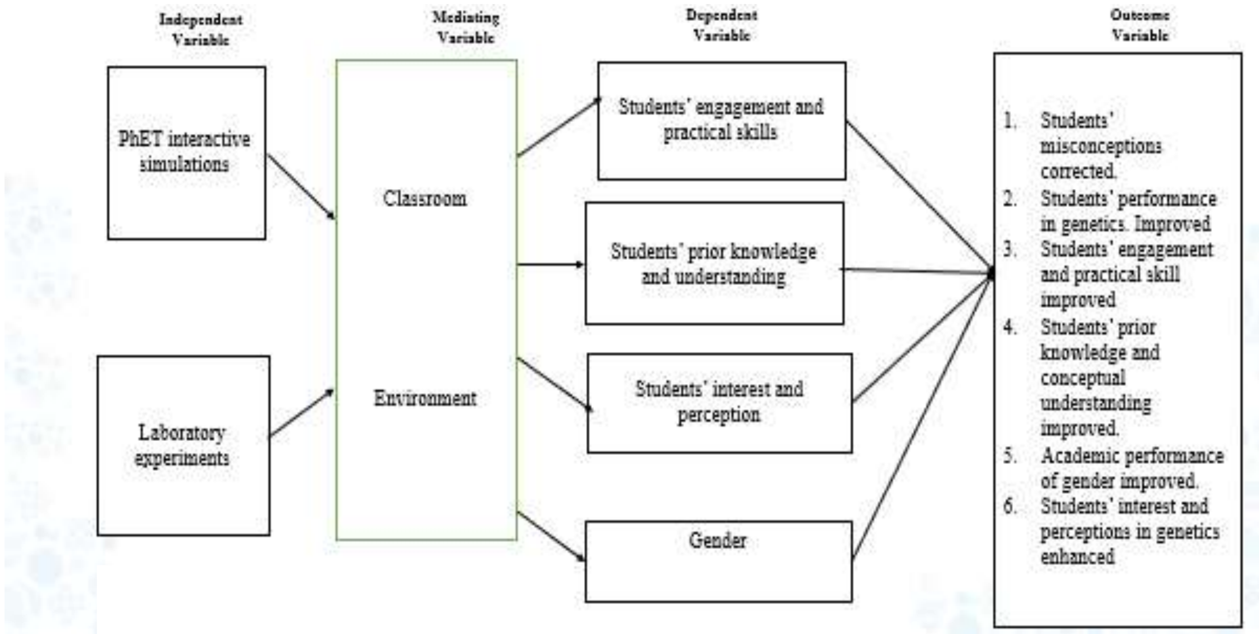

Figure 2: Conceptual framework of the study variables (Source: Researchers 'construct, 2024)

Interactive PhET simulations were incorporated in this study to support student learning through visually engaging and interactive experiences that strengthen conceptual understanding, encourage active exploration, and provide immediate feedback. These simulations were intended to bridge the gap between abstract genetic concepts and real-world phenomena, thereby making complex scientific ideas more accessible and easier to grasp for learners with different abilities and learning preferences. Consequently, exposure to PhET simulations was expected to improve students' academic performance, deepen their understanding, and increase their interest in genetics.

Laboratory experiments were also expected to enhance student learning by offering hands-on opportunities for inquiry, experimentation, and discovery. By engaging in practical exploration of selected genetics concepts, students were able to apply theoretical knowledge in authentic situations, strengthen critical thinking skills, and gain direct experience with scientific methods and procedures. These laboratory activities further encouraged collaboration, problem-solving, and the development of essential practical competencies that support scientific inquiry and research, ultimately contributing to improved academic performance (Figure 2). As a result, students involved in laboratory experiments were anticipated to demonstrate better performance, stronger conceptual understanding, and higher levels of engagement with the subject.

However, the conceptual framework recognises that the effectiveness of both PhET simulations and laboratory experiments may be shaped by factors such as instructional design, pedagogical strategies, learner characteristics, and contextual conditions. For this reason, future studies are encouraged to examine these variables and their possible interactions in order to develop a more comprehensive understanding of how simulation-based and hands-on learning approaches influence student outcomes.

Influence of PhET and laboratory experiments on improving students' academic performance

Both PhET simulations and laboratory experiments contribute to a framework that supports improved academic performance among students. A range of studies has consistently demonstrated that hands-on learning experiences, whether conducted in physical laboratories or virtual environments, strengthen students' understanding of scientific concepts and enhance their problem-solving abilities. Laboratory experiments provide tangible, real-world engagement that deepens conceptual understanding and fosters scientific inquiry. In contrast, PhET simulations offer interactive and visually rich experiences that cater to diverse learning preferences, enabling students to explore concepts more deeply and connect theoretical knowledge with practical applications.

For example, a quasi-experimental study by Sari and Guven (2013) investigated the effects of inquiry-based learning supported by interactive whiteboard activities, including simulations, animations, and videos, on students' academic achievement and motivation. The findings indicated that students exposed to these interactive tools performed better than those in traditional instructional settings, with a medium effect size. Similarly, Salame and Makki (2021) noted that computer simulations, being dynamic, interactive, and user-friendly, effectively support student-centred and inquiry-based teaching approaches.

Furthermore, combining laboratory experiments with PhET simulations has the potential to produce synergistic effects on student learning outcomes. Integrating both approaches allows learners to benefit from the distinct advantages of each method, resulting in a more comprehensive and enriched learning experience. For instance, students may initially engage in hands-on laboratory activities to develop foundational understanding in genetics and then use PhET simulations to explore more complex processes or to conduct virtual experiments that may be difficult or impossible to perform in a physical laboratory setting. This blended approach capitalises on the strengths of both modalities, ultimately fostering deeper understanding and improved academic performance.

Impact of PhET simulations and laboratory experiments on student engagement

Laboratory experiments significantly enhance student engagement in genetics by providing hands-on, real-world experiences that stimulate interest and curiosity. Through direct experimentation, students actively participate in the scientific process, which increases their motivation and enthusiasm for learning. These practical activities also cultivate a sense of scientific inquiry and discovery, as learners engage with authentic problems and develop solutions through investigation and experimentation.

In a similar way, PhET simulations promote engagement through interactive and visually stimulating learning experiences that appeal to students' curiosity and creativity. Recent studies have shown that interactive simulations improve the effectiveness of science instruction (Salame & Makki, 2021; Rutten, Van der Veen, & van Joolingen, 2015). Such simulations hold a distinctive place in science education because they create innovative learning environments that enhance teachers' instructional capacity while encouraging active student participation (Salame & Makki, 2021). The visual and dynamic features of PhET simulations capture students' attention and support active exploration of genetics concepts. Learners are able to manipulate variables, observe immediate outcomes, and conduct virtual experiments to test hypotheses. In addition, the provision of instant feedback enables students to evaluate their understanding and adjust their approaches accordingly. By offering a safe and accessible platform for experimentation, PhET simulations also promote learner autonomy, allowing students to engage with genetics concepts at their own pace.

Influence of PhET and laboratory experiments on students' knowledge and conceptual understanding of genetics

PhET simulations and laboratory experiments have a significant influence on students' knowledge acquisition and conceptual understanding of genetics. Laboratory experiments offer hands-on experiences that allow students to observe genetic phenomena firsthand, reinforcing theoretical concepts with practical applications. When students are engaged in experimentation, students develop a deeper understanding of genetic principles and processes, as well as critical thinking skills necessary for scientific inquiry.

PhET simulations on the other hand provide interactive and visual representations of genetic concepts, enhancing students' conceptual understanding through dynamic exploration. The visual nature of PhET simulations allows students to observe molecular processes, genetic interactions, and inheritance patterns in real-time, fostering intuitive understanding of complex genetic phenomena. Moreover, PhET simulations offer opportunities for active engagement and experimentation, enabling students to manipulate variables, test hypotheses, and explore genetic principles in a virtual environment.

Many learners experience difficulties when science is taught in an abstract form without connections to their everyday experiences (Ramma et al., 2018). Across educational levels, from basic to tertiary, science instruction often fails to adequately develop students' conceptual understanding, which in turn may reduce their interest in the subject (Perkins et al., 2014). In response to this challenge, online interactive simulations have been introduced as an innovative instructional tool. These simulations support learners in constructing and strengthening scientific understanding through guided exploration and discovery (Perkins et al., 2014). Wieman et al. (2016) found that simulations help students overcome misconceptions and develop more accurate and shared scientific understandings. In addition, Kotoka and Kriek (2014) reported that computer-based simulations are particularly effective in helping students grasp abstract scientific concepts.

Computer-based simulations are digital representations of processes that are difficult, dangerous, expensive, or impossible to observe directly, or that occur too quickly or too slowly for real-time observation (Makransky et al., 2017). Since their introduction into education, they have become a widely adopted instructional technology. In science education today, simulations and computers are considered as influential as traditional scientific instruments such as the microscope and telescope (Makransky et al., 2017). PhET simulations were developed with the dual purpose of increasing student interest and improving learning outcomes. They promote learning through interactive, animated, and game-like environments that encourage exploration (Wieman & Perkins, 2014). These tools highlight the relationship between real-world phenomena and scientific principles, while making expert mental models accessible by visualising otherwise invisible processes (Wieman & Perkins, 2014).

The PhET project was designed to transform science teaching and learning globally by providing free interactive simulations that are widely recognised for their effectiveness in improving science education (Banda & Nzabahimana, 2021a). These simulations aim to enhance student engagement and deepen learning in science subjects (Perkins et al., 2014). They foster active participation by allowing learners to construct knowledge through exploration in environments that support deep conceptual learning (Wieman et al., 2014). The interactive and game-like design of PhET simulations makes learning more enjoyable and encourages students to actively investigate scientific ideas. This process promotes cognitive engagement as learners build structured and meaningful understanding. As a result, PhET simulations stimulate curiosity and challenge students to explore concepts more deeply through interactive learning experiences (Perkins et al., 2014).

Conceptual understanding is defined as the ability to apply concepts, relationships, or representations appropriately in situations that require critical thinking (Balka et al., 2016; Balka, 2016). It also involves the capacity to derive meaning from known concepts and apply them in new contexts (Banda & Nzabahimana, 2021b). Learners with strong conceptual understanding do more than memorise facts; they comprehend scientific ideas and understand how and where these ideas apply. They organise knowledge coherently, which enables them to link new information to prior knowledge and construct meaningful understanding (Makransky et al., 2017).

Improving conceptual understanding in science requires teachers to adopt active learning strategies and design classroom environments that integrate modern instructional tools suited to learners' needs and labour market demands. Among these tools, interactive simulations such as PhET are widely recognised as effective in supporting conceptual development (Banda & Nzabahimana, 2021a). Evidence shows that PhET simulations significantly improve students' conceptual understanding in science subjects, particularly physics (Banda & Nzabahimana, 2021). Instructional strategies involving PhET include inquiry-based learning, virtual experimentation, problem-based learning, and scaffolded instructional approaches, as documented in studies across various educational contexts (Banda & Nzabahimana, 2021). To determine the effectiveness of PhET simulations on students 'achievement of the greenhouse effect, the PhET simulations were found to have a statistically significant positive contribution to the conceptual understanding of greenhouse effect. The study revealed that PhET simulations are simple to use and made the lesson quite enjoyable. The students need to experience PhET simulations at home and they had no difficulties using them. Therefore, the study concluded that despite its use of constructive teaching approaches, PhET, simulations provide a significant contribution to the learning process by empowering the instructional strategies (Makransky et al., 2017). Ndihokubwayo et al., (2020) discovered that PhET simulations and YouTube videos-based instructions are far more effective than traditional teaching in improving conceptual understanding of geometric optics in Rwandan secondary schools. As a result, they concluded that PhET simulations and Youtube video-based instructions are immensely helpful for Rwandan secondary school students doing physics in general, and optics in particular. The competence-based curriculum has shown a significant impact on classroom management and student learning (REB, 2018). Teachers are required to read more books and enrich their knowledge about various subjects and teach most updated lessons. In their teaching, teachers are expected to act as facilitators by applying learner centred teaching approaches where students are engaged and participate actively in the lesson (REB, 2018). Though the CBC implementation has provided significant opportunities in Rwandan education, there is insufficiency of teaching materials due to limited time to develop teaching aid, lack of some material in the surrounding environment as well as the high cost required to develop required instructional material (REB, 2018). This supported by the study conducted by Nsengimana, (2020) which revealed that

CBC content especially in science subjects are taught theoretically due to lack of appropriate teaching materials for teaching abstracts. However, Biology, being one of the science subjects to be taught in secondary schools, is not an exception to other science subjects such as chemistry and physics that are taught theoretically. Genetics, in particular, is one of the science subjects that students struggle to understand when taught without adequate instructional materials. Therefore, to solve this problem, new teaching approaches based on technology integration strategies are highly needed to reach the intended learning outcomes and improve conceptual understanding of sciences. To be more effective for PhET, the teacher should demonstrate all simulation features and students are given time to explore them. Students are encouraged to use computer and manipulate simulations. According to Banda and Nzabahimana (2021), some instructional methods of using PhET simulations to improve conceptual understanding include inquiry-based activities, virtualised experiments, problem-based learning activities, and scaffolded learning activities. This is based on a number of studies conducted in various countries and educational systems.

Influence of PhET and laboratory experiments on students' interest in genetics

Laboratory experiences have consistently offered learners opportunities to engage directly with the physical world through the use of equipment, models, tools, and scientific theories. Although science laboratories are typically structured environments where students follow set procedures using specific instruments and techniques, learner activities within these settings can take different forms. Laboratory instruction may involve physical manipulation such as biological dissections, chemical experiments, and interaction with tangible materials that can be explored through hands-on investigation. It may also include computer-based simulations that model processes which are difficult or impossible to observe directly, allowing learners to analyse otherwise inaccessible phenomena (NSTA, 2004). Examples include virtual biotechnology labs, molecular visualisation in chemistry, and simulations of plant and animal systems. Within such environments, students are able to design experiments, operate equipment, collect and record data, interpret results, and develop scientific reasoning skills (NSTA, 2004). Laboratory work has long been considered essential for developing a deeper understanding of science and for appreciating the nature of scientific inquiry (NRC, 2014).

In addition, laboratory settings provide learners with opportunities to develop both independent and collaborative skills. Students learn to divide tasks, assume different roles, share ideas, and engage in discussions of their findings. Because laboratory activities are intended to align closely with theoretical instruction, they help strengthen understanding of concepts and theories through practical experience (Makransky et al., 2017). Biology educators, in particular, emphasise the importance of laboratory work as a core component of teaching and learning, where students come to appreciate biology as an experimental discipline. Despite these advantages, traditional laboratory environments present several challenges, including equipment malfunction, high costs, limited space, safety concerns, and varying levels of student motivation and interest.

In response to these challenges, educators have attempted to improve laboratory experiences by making sessions more engaging, linking experiments more directly to theoretical content, and incorporating inquiry-based approaches. However, traditional "cookbook" laboratory activities often fall short in promoting meaningful learning, as they tend to emphasise procedural steps rather than the development of scientific understanding and inquiry skills (Bunterm et al., 2014). There is an increasing need for students to engage more deeply with scientific practices through inquiry-driven laboratory activities rather than passive execution of instructions (Lazonder & Harmsen, 2016). Inquiry-based laboratory instruction has been shown to improve both process skills and conceptual knowledge (Bunterm et al., 2014).

To address limitations in conventional laboratory teaching, PhET Interactive Simulations were developed under the leadership of Carl Wieman as part of a broader initiative to enhance science education. The project, established in 2002 at the University of Colorado Boulder, aims to provide virtual laboratory experiences through animated, interactive environments that encourage student exploration of scientific phenomena (Adams et al., 2015). Initially focused on physics, PhET has expanded to include chemistry, biology, mathematics, and earth science. With a mission to advance global science and mathematics literacy through free interactive simulations, the platform has been translated into more than 65 languages. Computer-based simulations offer an alternative to traditional laboratory work and have been shown to improve students' understanding of complex scientific concepts (Alsultanny et al., 2014). These simulations are dynamic digital models that represent real-world processes through animation, visualisation, and interactive features that support learning (Makransky et al., 2017). In science education, tools such as PhET are increasingly integrated into instruction and used to complement traditional teaching methods. Research suggests that PhET simulations are effective in supporting the teaching of biology at both secondary and tertiary levels (Lazonder & Harmsen, 2016). They enhance learning by providing visual representations, demonstrations, and interactive exploration opportunities that strengthen conceptual understanding (Makransky et al., 2017). In addition, they offer content support, procedural guidance, and reinforcement of affective learning outcomes (Moore et al., 2014). Studies further indicate that such simulations function as implicit scaffolding tools that support guided inquiry without overwhelming learners (Moore et al., 2018). Engagement with PhET simulations also encourages active exploration, which can lead to shifts in learners' understanding of scientific concepts and knowledge construction (Bing & Redish, 2012).

Laboratory experiments and PhET simulations play a crucial role in influencing students' interest in genetics. PhET simulations provide virtual environments where learners can engage with genetic concepts through dynamic, interactive models. These simulations offer visual representations of genetic processes, enabling students to manipulate variables, observe outcomes, and perform virtual experiments. Their interactive design promotes exploration and discovery, thereby stimulating curiosity and sustaining interest in genetics. In addition, PhET simulations are flexible and adaptable, allowing students to learn at their own pace and according to their level of understanding. The immersive features of these simulations capture attention and enhance engagement through visually rich and interactive experiences.

Supporting this, Salame and Makki (2021), in a study conducted in the United States of America, examined the impact of PhET simulations on students' learning outcomes and attitudes, as well as their most beneficial features. The findings indicated that PhET simulations were easy to use and provided enjoyable experiential learning opportunities that were not typically available in traditional laboratory settings. The study further revealed that PhET simulations improved students' conceptual understanding and contributed significantly to better academic performance, making them a valuable instructional tool (Salame & Makki, 2021).

Similarly, laboratory experiments provide hands-on experiences that align with students' natural curiosity and desire to investigate the physical world. Through direct experimentation, learners experience excitement and a sense of discovery as they explore genetic principles firsthand. Laboratory activities also create opportunities for collaboration and social interaction, as students work together to solve problems,

collect data, and interpret results. This cooperative aspect fosters a sense of shared learning and strengthens students' interest in genetics.
In addition, PhET simulations complement laboratory work by offering engaging and interactive experiences that stimulate imagination and curiosity. Their visual and dynamic nature enables learners to explore genetic processes in an immersive environment. By adjusting variables and observing immediate outcomes, students take greater control of their learning and develop a deeper conceptual grasp of genetics. Furthermore, the accessibility of PhET simulations allows students to continue exploring genetic concepts beyond the classroom, further enhancing their interest and enthusiasm for the subject.

Methods

Study Design and Setting

A convergent parallel mixed-methods design study was conducted at Bonzo Kaku Senior High School, Ellembele District, Ghana. The district is characterized by rural settlements and growing community education initiatives.

Population and Sample Size

The target population consisted of all form three (3) students at Bonzo Kaku Senior High School. Sample size Formula Adopted from Yamane (1967); Sample Proportion Formula adopted from Amofa (2025). So, the calculated sample size using Yamane's formula for a population of 450 with a margin of error of 5% is approximately 212.
The sample size was determined using Yamane's (1967) formula, which yielded a total of 212 students drawn from the population of 450. This sample size was considered adequate to ensure representativeness while maintaining feasibility for data collection and analysis.

$$n = \frac{N}{(1+(e)2}$$

Where:

- n = Sample size
- N = Population size
- e = Margin of error (expressed as a decimal, for example, 0.05 for 5%)

Using this formula, the sample size for a population of 450 with a margin of error of 5%.
Given:

- N=450
- e=0.05

Plugging in the values:

$$n = \frac{450}{(1+450)(0.05)2}$$

n = 211.76n ≈ 212

Sample Proportion Formula Used: $\frac{\text{Sample Frame}}{\text{Total Population}} \times$ Sample size

The sample size for this study was determined using Yamane's (1967) formula, while the sample proportion was guided by Amofa (2025). Applying Yamane's formula to a population of 450 students with a 5% margin of error produced an approximate sample size of 212 students.

Data Collection Instruments and Procedures

The study utilises test as one of the principal instruments in collecting data on students' academic performance in Genetics. Two tests were used for collecting data which were pre-intervention and post intervention tests. The researcher did not used an existing test by any testing agency but designed a new test known as Genetics Achievement Teacher Made Test (GATMT). The content of the two tests and difficulty level were the same, but the questions were different. The researcher used closed-ended questionnaires adapted from existing validated tools which were on a 5 Likert-scale type, to collect quantitative data. The researcher carried out a semi-structured face-to-face interview with the respondents in a focus group discussion to obtain data on their views about their attitudes toward the learning of Genetics using PhET interactive simulations and hands-on laboratory experiments.

Variables and Measures

The questionnaire is divided into four sections:

Section A: Students' Biographical Data

Section B: Causes of Students' Misconceptions in Genetics

Section C: Students' Interest in Using PhET and Laboratory Experiments to Teach Genetics

Section D: Students' Perception of Using PhET and Experiments to Teach Genetics

Data Analysis

Analytical techniques used for data analysis were descriptive statistics, one-sample t-test, paired sample t-test, two-way ANOVA, and thematic analysis, using SPSS version 26.

Ethical Considerations

Approval for this study was obtained from the University of Education, Winneba ethical review Board (UEWERB) with ethical clearance reference number-UEWC/33. Participation was voluntary, with confidentiality.

Results

Table 7 : *Demographic Information on Participants*

Table 12: *Wilcoxon Paired Sample t-test Results*

Table 13: *Mann-Whitney U Test Results*

Table 20: *Summary of the Results*

Table 7: Demographic Information on Participants

Variable	**Category**	**Counts**	**Percent**
Gender	Female	145	68%
	Male	67	32%
	Total	**212**	**100%**
Age	17-18	67	32%
	15-16	142	67%
	19 Years and Above	3	1%
	Total	**212**	**100%**
Residential Status	Boarding	146	69%

	Day	66	31%
	Total	**212**	**100%**
Parental Level of Education	No Formal Education	26	12%
	Primary	55	26%
	Secondary	93	44%
	Tertiary	38	18%
	Total	**212**	**100%**

From the descriptive statistics as presented in Table 7, majority of the respondents were females (68%) while males represented only 32%. In terms of age, most students were between ages 15 – 16 years (67%) followed by those aged 17 – 18 years (32%). Only one responded (1%) was 19 years or above. When it comes to residential status, 69% of the respondents were boarding students, while 31% were day students. For parental level of education, a large proportion of the students (44%) had parents with only secondary education while 26% had parents with primary education. A smaller number of students had parents with no formal education (12%) or tertiary education (18%).

Research Question Three/ H_{o1}

H_{o1}: *Both PhET simulation and laboratory experiment will have no significant impact on students' performance in genetics and laboratory skills*

This hypothesis proposes that PhET simulation and laboratory experiments will have no statistically significant impact on students' performance in genetics and laboratory skills. Simply put, the differences in both pretest and posttest scores will be equal to zero (H_o: μPretest - μPosttest = 0), while the alternative hypothesis proposes that PhET simulation and laboratory experiments will have a statistically significant impact on students' performance in genetics and laboratory skills. That is, the difference between pretest and posttest scores will not be equal to zero (H_a: μPretest - μPosttest $\neq$ 0).

To test this hypothesis, a paired sample t-test was conducted. The independent was the intervention categorized into two conditions: the period before the PhET simulation and laboratory experiments were implemented, and the period after they were implemented. The dependent variable was genetic performance and laboratory skills measured.

Prior to performing the main test, a normality test and outlier detection were conducted. There were no issues with outliers; however, the normality assumption was violated for both the pretest and posttest scores *($W = .982, p = .009$)*, and for pre-laboratory and post-laboratory skills *($W = .834, p < .001$)*. Based on this, a non-parametric Wilcoxon rank test was performed. This test compares the medians of the pretest and posttest to determine whether there is a significant difference. The median is used because it is more robust to violations of normality compared to the mean. Table 12 below presents the paired sample t-test results.

Table 12

Wilcoxon Paired Sample t-test Results

Condition	Median	SD	Median Diff.	W	P	Effect Size	Impact Score
Pretest	14	4.12	-23	0	<.001	-1.00	46%
Posttest	37	5.87					

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Pre-Lab	3	0.86	-5	147	<.001	-0.987	50%
Post-Lab	8	1.85					

Note. Impact score (IS) = $\frac{\text{Posttest Median Score} - \text{Pretest Median Score}}{\text{Total Score}} \times 100$

The Wilcoxon paired sample t-test results as presented in Table 12, show that there is a statistically significant increase in genetics scores after the implementation of PhET simulation and laboratory experiment. The median score before implementation was significantly lower (Median = 14, SD = 4.12) than the median score after implementation (Median = 37, SD = 5.87), W = 0, $p < .001$ (two-tailed). Before the intervention students' performance was 28%; however, after the intervention, it rose to 74%. The calculated impact score was 46%, which means that on average, the intervention has improved students' understanding of genetics by 46%. The rank biserial correlation, which measures the size of the impact, was -1.00 indicating a large impact. This suggests there is a 100% chance that a randomly selected student after the intervention will score higher than a randomly selected student before the intervention.

Also, in terms of the laboratory skills, the paired sample t-test results show that there is a statistically significant increase in laboratory skills after the implementation of the PhET simulation and laboratory experiment. The median score after implementation (Median = 8, SD = 1.851) was significantly higher than the median score before implementation (Median = 3, SD = 0.856); W = 147, $p < .001$ (two-tailed). Before the intervention, students' laboratory skills were 30%; however, after the intervention, skills rose to 80%. On average, the intervention has improved students' laboratory skills by 50%. This was confirmed by the rank biserial correlation, which measures the size of the impact. It was found to be -0.987, indicating that there is a 99% chance that a randomly selected student after the intervention will demonstrate higher laboratory skills than a randomly selected student before the intervention.

These results suggest that both the PhET simulation and laboratory experiment contributed significantly to improving students' genetic scores and laboratory skills. Hence, the null hypothesis is rejected in favour of the alternate hypothesis, confirming that the use of PhET simulation and laboratory experiment has a profound positive impact on students' genetic performance and laboratory skills.

Research Question Four/H_{02}

H_{o2}: There will be no statistically significant difference between male and female students' posttest scores in genetics and laboratory skills.

The above hypothesis proposes that gender will have no significant influence on students' genetic post-test scores and laboratory skills, meaning male and female post-test scores and laboratory skills will be equal (Ho2: μ Female = μ Male), while the alternate hypothesis proposes that gender will have a significant influence on students' post-test scores in genetics and laboratory skills, meaning that there will be a significant difference between male and female students' post-test scores and laboratory skills (Ha2: μ Female $\neq$ μ Male).

To test this hypothesis, a two independent samples t-test was used. The independent variable was gender, grouped into male and female, while the dependent variables were the post-test scores and post-laboratory skills. Before the main test, three major assumptions were checked: normality, homogeneity or equality of variance, and outlier detection was done. The Shapiro-Wilk test was conducted to assess whether the post-test scores and laboratory skills followed a normal distribution. The results indicated that the data violated the normality assumption.

However, the Levene's test for homogeneity of variance showed that the spread of post-test scores and post-laboratory skills between male and female students was not significantly different, confirming that the assumption of homogeneity was met. Additionally, no extreme outliers were detected, confirming that the dataset was appropriate for analysis. Based on the violation of the normality assumption, a non-parametric Mann-Whitney U test was used. This test compares medians for both groups rather than means. Table 13 below presents the results.

Table 13
Mann-Whitney U Test Results

Condition	Group	Median	SD	Diff.	U	P	Effect Size	Impact Score
Posttest	Female	39	5.33	6	2945	<.001	-.394	12%
	Male	33	6.05					
Post lab	Female	8	2.06	1	3728	0.005	-.233	10%
	Male	7	1.28					

From the Mann-Whitney U Test Results as presented in Table 13, the results demonstrate that there is a statistically significant difference between male (Median = 33, SD = 6.05) and female (Median = 39, SD = 5.33) students' post-test scores in genetics; U = 2945, $p < .001$. The results indicate that the males' performance in genetics after the intervention was 66%, while the females was 78%, showing a difference of 12%. This indicates that, on average, females scored 12% higher than the males. The Cohen's *d* statistic, which measures the effect size, was found to be -0.394, indicating a small effect. This means that a randomly selected female student has a 65% chance of scoring higher than a randomly selected male student after the intervention. This implies that if a teacher were to randomly select a student and that student happened to be female, there would be a 65% likelihood that she would outperform a randomly selected male counterpart.
Also, from Table 13, the Mann-Whitney U-test shows that there is a statistically significant difference in post-laboratory skills between male (Median = 7, SD = 1.28) and female students (Median = 8, SD = 2.06); U = 3728, $p = .005$. The females' laboratory skills after the intervention were 80%, while the males were 70%, with a difference of 10%. This means that, on average, females' laboratory skills improved by 10% more than males. Additionally, the effect size was 0.233, suggesting a 56% chance that a randomly selected female student would have higher post-laboratory skills than a randomly selected male student.
Based on the above results, the null hypothesis is rejected in favour of the alternate hypothesis, concluding that the PhET simulation and laboratory experiment benefited the females more than the males in terms of genetics scores and laboratory skills acquisition.

Table 20: ***Summary of the Results***

Research Question / Hypothesis	Key Finding	Conclusion
RQ3/H_01: PhET simulation and laboratory experiment will have no significant impact on students'	Students' genetics performance improved significantly after the intervention. Scores increased from 28% before the intervention to 74% after the intervention. Laboratory skills also improved from 30% to 80%. Both results were statistically significant.	The null hypothesis was rejected. PhET simulation and laboratory experiment significantly improved students' genetics

genetics and lab performance.		achievement and laboratory skills.
RQ4/H_02: There will be no statistically significant difference between male and female students' performance.	Female students performed better than male students in both genetics' achievement and laboratory skills after the intervention.	The null hypothesis was rejected. Female students benefited more from the intervention than male students.

Key Findings

1. Also, the study found that there was a statistically significant improvement in students' genetics scores following the use of PhET simulation and laboratory-based instruction. Post-intervention scores were higher than pre-intervention scores, indicating improved conceptual understanding. A similar pattern was observed in laboratory skills, where students recorded higher post-intervention scores compared to pre-intervention performance. The differences observed in both cases were statistically significant, suggesting that the combined intervention had a positive effect on both cognitive and practical learning outcomes.
2. In addition, the study found gender differences in both genetics achievement and laboratory skills. Female students recorded higher post-intervention scores in genetics compared to male students. A similar pattern was observed in laboratory skills, where females again performed better than males. These differences were statistically significant, indicating that gender was associated with variation in performance under the same instructional conditions.

Conclusion

The study provides evidence that combining PhET simulation with laboratory experience improves students' understanding and practical performance in genetics. Although the improvement is not uniform across learners. Students showed stronger performance in recall-based tasks than in application-based tasks. This indicates a persistent difficulty in applying genetic concepts to unfamiliar situations. After the intervention, both genetics achievement and laboratory skills improved significantly, with female students generally recording higher post-intervention scores in genetics, while differences in laboratory skills were less consistent. Students also expressed positive views about the intervention, describing it as more engaging and helpful in making abstract genetic concepts easier to understand.

Recommendations

1. The overwhelmingly positive student feedback on the use of PhET simulations and laboratory activities signals a critical shift in how genetics should be taught. These interactive tools not only enhanced comprehension but also improved learner motivation and participation. As such, it is

recommended that schools formally incorporate digital simulations and simplified laboratory experiences into the core science curriculum. Even in settings with limited infrastructure, basic strategies such as the use of projected simulations, printed snapshots and guided discussions can support meaningful learning. Integration of such tools should not be treated as optional enrichment but as fundamental to science teaching practice.

2. Empirical results from this study showed a dramatic improvement in student learning outcomes following the intervention, reinforcing the argument that traditional pedagogical practices focused on rote memorization and fast-paced syllabus coverage are insufficient. It is therefore recommended that curriculum developers reconsider the structure and pacing of science content, allowing more room for active learning strategies such as collaborative tasks, inquiry-based exploration, and student reflection. A well-designed curriculum must prioritise conceptual understanding over coverage, and promote deep, experiential engagement with scientific content rather than a superficial rush to meet exam deadlines.

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