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þÿEnhancing Grade 11 Students Conceptual Understanding of Genetics through Technology-Enhanced Guided Inquiry-Based Learning

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MED THESIS ON

ENHANCING GRADE 11 STUDENTS' CONCEPTUAL UNDERSTANDING OF GENETICS THROUGH TECHNOLOGY-ENHANCED GUIDED INQUIRY-BASED LEARNING

By: Neway Atlaw Beyene

June 2026

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Enhancing Grade 11 Students' Conceptual Understanding of Genetics through Technology-Enhanced Guided Inquiry-Based Learning

By

Neway Atlaw Beyene

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science Education in Focused of Biology

Advisor- Mersha Minwuyelet (PhD, Asst Professor)

June 2026

BAHIR DAR, ETHIOPIA

DECLARATION

I, the undersigned, declare that this thesis work, entitled "Enhancing Grade 11 Students' Conceptual Understanding of Genetics Through Technology-Enhanced Guided Inquiry-Based Learning" submitted in partial fulfillment of the requirements for a Master of education in Science focused in biology, is a record of original work completed by me and has never been submitted to this or any other institution to receive any other degree or certificate.

Neway Atlaw	**June, 2026, Bahir Dar University**	________________
Name of the candidate	**date, and place**	**Signature**

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APPROVAL OF THESIS FOR DEFENSE

We hereby certify that I have supervised, read, and evaluated this thesis entitled **“**Enhancing Grade 11 Students’ Conceptual Understanding Of Genetics Through Technology-Enhanced Guided Inquiry-Based Learning**”** prepared under my guidance. I recommended the Thesis be submitted to oral defense.

Approval of thesis proposal for defense

Mersha Minwuyelet (PhD, Asst. Prof.)	____________________	June 30, 2026
Advisor’s name	Signature	Date
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APPROVAL OF THESIS FOR DEFENSE RESULT

As members of the head of examination, we examined the thesis entitled “Enhancing Grade 11 Students’ Conceptual Understanding Of Genetics Through Technology-Enhanced Guided Inquiry-Based Learning” by Neway Atlaw. We hereby certify that the dissertation is accepted for fulfilling the requirements for the award of the “Master of Education in Science focused in Biology”.

Board of Examiners

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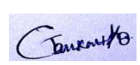
Million Tadesse		June 28, 2026
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Acronyms

DBR	Design Based Research
DNA	Deoxyribonucleic Acid
FDRE MoE	Federal Democratic Republic of Ethiopia Ministry of Education
GIBL	Guided Inquiry-Based Learning
GMO	Genetically Modified Organism
IBL	Inquiry-Based Learning
RNA	Ribonucleic Acid
TE-GIBL	Technology-Enhanced Guided Inquiry-Based Learning

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Abstract

Genetics remains one of the most conceptually demanding domains in secondary school biology, where persistent misconceptions and abstractness of content often delay meaningful learning. This study examined the effectiveness of Technology-Enhanced Guided Inquiry-Based Learning in strengthening Grade 11 students' conceptual understanding of genetics and reducing persistent misconceptions, employing a mixed-methods approach within a Design-Based Research framework. 50 Grade 11 students participated in the intervention, and a researcher-developed two-tier diagnostic test was administered before and after the implementation of intervention to assess understanding of genetics, while focus group discussions, classroom observation and semi-structured interviews provided qualitative depth. Quantitative analysis revealed a statistically significant improvement in post-intervention performance, $t(49) = 5.763$, $p < .001$, *with a large effect size (Cohen's* $d = 0.815$*), and domain-level analyses confirmed meaningful gains across all areas, with the most notable progress observed in meiosis, gametes, and fertilization. Misconception analysis further demonstrated a considerable shift toward scientifically accurate conceptions following the intervention. Qualitatively, students described the technology-supported activities including simulation videos and animations as engaging and instrumental in visualizing abstract biological processes, while also reporting increased motivation and greater confidence in their learning. Collectively, these findings suggest that Technology-Enhanced Guided Inquiry-Based Learning is a promising instructional approach for promoting conceptual change and reducing misconceptions in genetics, with broader implications for teaching other challenging topics in secondary school biology.*

Keywords: Conceptual understanding, design based research, misconceptions, Technology-Enhanced Guided Inquiry-Based Learning, two-tier diagnostic test

CHAPTER 1 INTRODUCTION

1.1 Background of the Study

Abilities of people to understand the world they live on and work depend on their understanding how science produces reliable knowledge, for most people such understanding comes from education (Nurse, 2016). Education represents the domain through which human kind proceed to transmit, consolidate and develop in to human culture, the ensemble of knowledge systems, science, arts, values and religions (Younès & Vohra, 2000). The big progress in science education in the last few decades has changes our perception about scientific disciplines, science education has been identified as the major bed rock for sustainable development of nations as it is majorly concerned with important knowledge and skills in environment and other aspects (Ibrahim Ahmad, 2018).

The recent history of human society shows how scientific and technological progress has helped to trigger social, economic and cultural development. In the 19th century, advancement in physics and engineering helped to the industrial evolution. In 20th century, advancement in agricultural science, genetics and animal and plant breeding provides bases for green revolution; new knowledge in microbiology, immunology medical and pharmacological science helped to reduce the occurrence of diseases (Younès & Vohra, 2000). The discovery of the DNA structure and function ignited a biological revolution continue to expand during the 21st century. Biology education is playing increasingly a vital role in the world educational system. As a fundamental field of study it significantly contributes to cultivating students' environmental awareness, ecological ethics, and social responsibility (Hu et al., 2025).

With the current discoveries and innovation of molecular structure of DNA, genetics has become one of the most important subject in the area of research and biotechnology that speed up the evolutionary development of many applied fields like medicine, agriculture, animal husbandry, and especially industry (Kılıç Mocan, 2021). This biology concept is also essential for understanding some controversial issue related to cloning, genetically modified organisms (GMOs), selection of sex, among others, and it has been appearing in human lives more frequently than ever before (Ojo, 2024).

The Federal Democratic Republic of Ethiopia Ministry of Education understood this need and tries to make genetics well-established curricula, even at secondary level (*Biology Syllabus , Grade 11*, 2009). At the secondary level, genetics is one of the several concepts that are thematically thought in biology. It consist topics like the genetic materials, the structure and function of DNA and RNA, the process of cell division, protein synthesis, Mendelian inheritance, sex determination, and non-Mendelian inheritance. The sub-topics found under genetics in Ethiopian grade 11^{th} chapter 4 biology text books include the structure and function of DNA and RNA, DNA replication, Mendelian crosses and Co-dominance, Incomplete dominance and Multiple alleles (FDRE MoE, 2023). It is one of the concepts that help to students acquire abilities like reasoning, problem solving and reflective thinking. Additionally genetics course helps the progression of student from simple concepts comprehension to more sophisticated levels of understanding, and allowed integration of newly learned content into their previous understandings (Cisterna et al., 2013).

Being such important subject to be learned in school, genetics is one of the usually considered the difficult and misunderstood subject by the students (Gusmalini et al., 2020; Machová & Ehler, 2023). The topics are difficult for student learning because they are complex and abstract (Cisterna et al., 2013; Clough & Wood-Robinson, 1985; Duncan et al., 2009; Duncan & Reiser, 2007; Stewart, 1982; Tsui, C. Y., y Treagust, 2005). Moreover, misconceptions presented another challenge for secondary school students

Misconception in genetics concepts are found on the meaning and scope of genetics concepts, genetic material (genes, DNA, and chromosomes), gene-DNA-chromosome relationships, protein synthesis processes, heredity principles, inheritance mechanisms, sex determination, relationship meiotic and meiosis division with inheritance, and mutations (Gusmalini et al., 2020). This misconception can occur due to several factor, in general these factors are students, teachers, books, context, and teaching methods (Gusmalini et al., 2020).

Based on the national educational assessment and examinations agency, Ethiopian third national learning assessment of grade 10 and 12 students result observation, the academic achievements of students in biology subject as measured by percent mean score and the composite mean score was 38.33% for grade 10 and grade 12 Biology was 50.01%. This result is below the minimum requirement that the students are expected to achieve. Because, the minimum passing mark for each subject set by the Education and Training Policy is 50% (MoE, 2017). When the achievement of grade 12 students by content domain in percent mean score is studied, students score the lowest 42.72% in genetics than in behavior, biochemical molecules, cell biology, ecology, energy transformations, enzymes, evolution, microorganisms and the science of biology (MoE, 2017).

In many secondary school contexts, genetics instruction is dominated by teacher-centered approaches, such as lectures, note copying, and routine problem-solving exercises (Hmelo-silver et al., 2007; Kirschner et al., 2010). Traditional lecture-based teaching methods often fall short in fostering and enhancing deep understanding, leading to persistent misconceptions among secondary school students (Duncan & Reiser, 2007). These teaching strategies have little effect on students' acquisition of meaningful understanding of genetics concepts (Banet & Ayuso, 2000; Stewart, 1982).

There is a need to develop other methods that are effective to teach genetics and enhances the understanding of students about the concept. Among the methods, inquiry-based learning (IBL) has been widely advocated in science education as an instructional approach that engages learners in scientific practices and supports deeper conceptual understanding. Inquiry-based instruction encourages students to ask questions, investigate phenomena, analyze data, and build explanations based on evidence, aligning with constructivist views of learning (NRC, 2000). Different empirical studies and meta-analyses indicate that when compared with traditional instructional methods, IBL can positively influence students' conceptual understanding, engagement, and reasoning skills (Lazonder & Harmsen, 2016).

Having such uses, different research cautions inquiry learning is not uniformly effective when implemented without sufficient instructional support. Meta-analytic evidence indicate that guided inquiry, which incorporates scaffolds such as prompts, structured tasks, feedback, and teacher facilitation, produces significantly stronger learning outcomes than minimally guided or unguided inquiry, particularly for complex scientific domains and novice learners (Lazonder & Harmsen, 2016). Without guidance, students may experience excessive cognitive load, focus on irrelevant aspects of tasks and become disoriented during investigations.

Beside pedagogical innovations, advances in educational technology have expanded possibilities for supporting science learning. Among which the use of computer simulations to teach in the class room is the common method implemented (Kapici, 2025). It is well accepted that the principles of genetics cannot easily be learned only from lectures, even with excellent descriptive textbooks (Sved, 2010). Computer simulations and interactive digital environments can make abstract biological processes visible, allow manipulation of variables, and provide immediate feedback, which is especially valuable in genetics education where many processes cannot be directly observed (Angelo et al., 2014; R. L. Bell et al., 2017). Computer-based learning environments provide practical opportunities for learners to apply their domain knowledge and enhance their critical and higher-order thinking skills (De Jong, 2006).

However, studies emphasis that technology alone does not guarantee improved learning outcomes. The effectiveness of simulations depends critically on how they are integrated into instruction. Studies show that simulations are most effective when embedded within structured pedagogical frameworks like guided inquiry where students receive explicit support for planning investigations, interpreting results, and linking evidence to scientific explanations (R. L. Bell et al., 2017; Deep et al., 2020). When used without pedagogical guidance, simulations may lead to superficial exploration rather than conceptual understanding.

This study has adopted a Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) approach, refined through Design-Based Research, to enhance Grade 11 students' conceptual understanding of genetics. By integrating guided inquiry pedagogy with carefully structured multimedia. The study reported an improved learning outcomes and empirically grounded design principles for effective genetics instruction in secondary schools.

1.2 Statement of the Problem

Genetics is the central component of secondary school biology because it is used in many modern applications in medicine, agriculture, biotechnology and enhance students' ability about contemporary scientific issues (Kılıç Mocan, 2021; Machová & Ehler, 2023). Despite its importance, genetics is widely regarded as one of the most difficult topics for secondary students due to its abstract and complex nature (Cisterna et al., 2013; Clough & Wood-Robinson, 1985; Duncan et al., 2009; Duncan & Reiser, 2007; Gusmalini et al., 2020; Machová & Ehler, 2023; Stewart, 1982; Tsui, C. Y., y Treagust, 2005). Students often struggle to understand the relationships among genes, chromosomes, DNA, and traits, as well as to connect molecular, cellular, and organismal levels of explanation (Clough & Wood-Robinson, 1985; Duncan et al., 2009; Duncan & Reiser, 2007; Kılıç Mocan, 2021; Stewart, 1982; Tsui, C. Y., y Treagust, 2005). These difficulties reveal a theoretical gap between the coherent, multilevel understanding envisioned by learning-progression research and the fragmented knowledge structures held by many secondary students.

Empirical studies indicate that misconceptions in genetics are not random errors but stable, high-confidence alternative conceptions. Using the Certainty of Response Index, Gusmalini et al., (2020) found that many students were highly confident in incorrect understandings of fundamental genetics concepts, suggesting that conventional instruction is often ineffective in challenging these ideas. Such misconceptions frequently persist even after formal teaching, highlighting the difficulty of promoting conceptual change in genetics (Machová & Ehler, 2023; Tsui, C. Y., y Treagust, 2005).

In Ethiopia, genetics is taught in Grade 11 biology to develop students' reasoning, problem-solving, and reflective thinking skills. However, national learning assessments indicate that students' biology achievement remains below the expected standard. The Third National Learning Assessment reported mean scores of 38.33% for Grade 10 and 50.01% for Grade 12 biology, with genetics recording the lowest content-domain score (42.72%) among Grade 12 students (MoE, 2017). These findings reveal a gap between the intended curriculum outcomes and students' actual learning in genetics.

Classroom level factors appear to contribute to this situation. Genetics is a topic that cognitively demanding abilities like hypothesis-testing approach, the ability to handle abstract and invisible processes, and the coordination of ideas across multiple levels of biological organization (Baker & Lawson, 2001; Duncan et al., 2009; Duncan & Reiser, 2007). But, in many secondary school, the instruction is dominated by teacher-centered lecturing, textbook exposition, and algorithmic practice with routine problems, with limited opportunities for students to investigate phenomena, test ideas, or explicitly confront their misconceptions (Banet & Ayuso, 2000,; Hoppe, 2013; Kılıç Mocan, 2021; Knippels et al., 2005). Traditional achievement tests are commonly used to reveal misconception than specifically designed tools like tow-tier or confidence response index (Gusmalini et al., 2020). This reduces teachers' ability to identify and address underlying students' misconceptions.

The researcher's classroom observations in Grade 11 biology revealed that genetics instruction is largely teacher-centered; relying on lectures, note copying, and routine exercises such as Punnett squares. Although these practices help students perform algorithmic tasks, they provide limited opportunities to investigate mechanisms or construct evidence-based explanations. Consequently, many students show procedural competence without deep conceptual understanding, particularly regarding meiosis, inheritance patterns, and genotype–phenotype relationships. This observation is consistent with studies showing that students can solve genetics problems successfully while lacking mechanistic understanding (Chattopadhyay, 2005; Santosa & Ratih, 2024).

Informal discussions with students revealed that many perceive genetics as confusing, highly abstract, and filled with difficult terminology. Students particularly struggle to visualize processes such as chromosome segregation and recombination and to relate these processes to observable inheritance patterns. These perceptions are consistent with evidence showing that inadequate visualization and weak conceptual connections are major contributors to difficulties in learning genetics (R. L. Bell et al., 2017).

Teachers also report challenges in teaching genetics effectively, including limited instructional time, large class sizes, and difficulties in providing concrete representations of abstract biological processes. Consequently, many rely on lecture-based instruction because of curriculum demands and limited laboratory or technological resources. Such constraints often hinder the implementation of student-centered and inquiry-based approaches, despite teachers' recognition of their potential benefits (Santosa & Ratih, 2024).

Traditional teaching approaches in Ethiopian secondary schools have been inadequate for addressing the abstract nature of genetics and persistent student misconceptions. Although inquiry-based learning (IBL) can enhance engagement and conceptual understanding, evidence shows that inquiry alone is insufficient. Minimally guided inquiry may impose excessive cognitive demands, especially in complex topics such as genetics (Baker & Lawson, 2001; Knippels et al., 2005; Lazonder & Harmsen, 2016; Thomson & Stewart, 1985). Therefore, inquiry activities need structured guidance to promote meaningful conceptual learning.

Educational technologies, particularly computer simulations, can support genetics learning by providing dynamic visualizations and opportunities to explore abstract processes. However, technology alone does not ensure improved learning outcomes. Research indicates that simulations are most effective when integrated into guided inquiry environments that provide explicit scaffolding for hypothesis generation, data interpretation, and scientific reasoning (R. L. Bell et al., 2017; Deep et al., 2020). Without such pedagogical support, technology use may remain superficial and fail to address students' underlying misconceptions.

Several studies have examined inquiry-based learning, guided inquiry, and technology-enhanced instruction independently but there is limited context-sensitive research that systematically combines these elements into a coherent instructional design and examines how such a design can be refined through classroom implementation. This study tried to integrate guided inquiry and educational technology through iterative DBR processes.

1.3 Basic Research Questions

This study was guided by the following research questions:

1. What is the initial level of Grade 11 students' conceptual understanding of selected genetics concepts, and what common misconceptions do they hold?

2. What effect does Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) have on Grade 11 students' conceptual understanding of selected genetics concepts?
3. What effect does Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) have on reducing Grade 11 students' misconceptions about selected genetics concepts?

1.4 Objectives of the Study

1.4.1 General Objective

The general objective of this study was to investigate the effectiveness of a Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) in enhancing Grade 11 students' conceptual understanding of genetics, reducing their misconceptions and to compare with conventional teaching methods.

1.4.2 Specific Objectives

This study aimed at;

1. To determine the initial level of Grade 11 students' conceptual understanding of selected genetics concepts and identify the common misconceptions they hold.
2. To examine the effect of Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) on Grade 11 students' conceptual understanding of selected genetics concepts.
3. To investigate the effect of Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) on reducing Grade 11 students' misconceptions about selected genetics concepts.

1.5 Significance of the Study

This study is expected to be significant for students, teachers, school leaders and curriculum developers and researchers and policy makers.

For students, this study is expected to enhance conceptual understanding of genetics by moving learning beyond rote memorization toward meaningful explanation and scientific reasoning. Through technology-supported guided inquiry activities, students are provided with opportunities to visualize abstract processes, test ideas, interpret evidence, and construct coherent explanations. Such learning environments have been shown to be particularly effective for complex topics like genetics, where misconceptions are prevalent and difficult to overcome through conventional instruction.

The integration of technology within guided inquiry is expected to reduce cognitive barriers by making invisible biological processes visible and interactive, thereby facilitating conceptual understanding and minimizing misconceptions related to meiosis, inheritance patterns, and genotype-phenotype relationships (R. L. Bell et al., 2017; Rutten et al., 2012). Consequently, students may achieve better learning outcomes, increased engagement, and greater confidence in understanding genetics concepts.

For biology teachers, this study provides a practical framework for implementing inquiry-based learning with appropriate guidance and technological support. The TE-GIBL model offers adaptable lesson structures, scaffolding strategies, and activity designs that can help teachers address challenges related to time constraints, classroom management, and limited instructional resources. By documenting implementation practices and challenges, the study also provides insights into effective ways of facilitating inquiry, classroom discourse, and the meaningful use of simulations.

At the school and curriculum level, the study provides context-sensitive evidence on the effectiveness of TE-GIBL in improving students' conceptual understanding of genetics. The findings can support instructional decision-making, curriculum development, and the adoption of low-cost digital tools, particularly in resource-constrained settings where laboratory facilities are limited.

From a research perspective, the study contributes to the literature on guided inquiry and technology-enhanced science education through a Design-Based Research (DBR) approach. By combining quantitative evidence of learning gains with qualitative evidence of classroom processes, it generates design principles that explain not only whether TE-GIBL works, but also how and under what conditions it can be effectively implemented. Such contributions are especially valuable in under-researched contexts and can inform both educational practice and theory.

1.6 Scope and Delimitation of the Study

This study was delimited in terms of content, participants and setting, time frame, and methodology.

Content scope

The study was focused on selected genetics concepts included in the Ethiopian Grade 11 biology curriculum, such as the genetic materials, the structure and function of DNA and RNA, the process of cell division, protein synthesis, Mendelian inheritance, sex determination, and non-Mendelian inheritance. It emphasized students' conceptual understanding and misconceptions about these core ideas.

Participants and setting

The study has involved Grade 11^{th} D students from Fasilo secondary schools that follow the Ethiopian national curriculum.

Time frame

The intervention was implemented during the regular teaching period allocated to the genetics unit in the school academic calendar. Data collection (pre-tests, post-tests, observations and group discussion) was conducted within this limited period; long-term retention and delayed effects beyond the unit are outside the scope of the present study.

Methodological delimitation

The research employed Design based research (DBR) with intact classes rather than randomly assigned individuals, which may limit the degree of control over pre-existing group differences. Conceptual understanding and misconceptions was assessed primarily through written diagnostic tests, supported by classroom observations and student perception questionnaires. Other possible influences on learning such as home background, prior exposure to technology, or teacher beliefs are acknowledged but not investigated in depth.

By clearly defining these boundaries, the study aimed to generate focused and contextually relevant evidence on the effectiveness of a Technology-Enhanced Guided

Inquiry-Based Learning (TE-GIBL) approach for teaching genetics in Grade 11, while recognizing that its conclusions should be interpreted within these delimitations.

1.7 Limitation of the study

Although the study was carefully designed to examine the effect of TE-GIBL approach on enhancing Grade 11 students' conceptual understanding and minimizing their misconception of genetics, several limitations were acknowledged:

The study was conducted in one intact class; As a result, the findings may not fully represent all Ethiopian schools, especially those with very different resource levels, class sizes, or contexts. Generalization to other regions or countries should therefore be made with caution.

The instructional intervention was confined to the teaching duration of the genetics unit within one academic term. This relatively short time frame might be sufficient to detect immediate changes in conceptual understanding and misconceptions but might not capture long-term retention or the stability of conceptual change over time.

Conceptual understanding and misconceptions were measured primarily through written diagnostic tests and self-report questionnaires. Although the instruments were carefully designed and piloted, they cannot fully capture all dimensions of students' thinking, reasoning strategies, or affective responses. There was also the possibility of guessing or social desirability bias in students' responses.

Recognizing these limitations will helps to frame the interpretation of the findings and points to directions for future research that could address them for example, by involving more schools, extending the time frame, or using mixed-method designs that explore students' reasoning processes in greater depth.

1.8 Operational Definitions of Key Terms

For the purpose of this study, the following key terms are defined operationally as they are used in the research:

Conceptual understanding: refers to Grade 11 students' scientifically accurate grasp of core genetics concepts and their ability to explain relationships among these concepts, make predictions, and justify answers using appropriate biological reasoning.

Misconception: is defined as a scientifically incorrect idea or explanation about a genetics concept that is held with some degree of confidence and consistency by the learner.

Genetics concepts: in this study refer to the set of topics covered in the Grade 11 biology curriculum related to heredity and molecular genetics.

Inquiry-Based Learning (IBL): is a student-centered instructional approach in which learners actively engage in questioning, investigating phenomena, analyzing evidence, and constructing explanations rather than passively receiving information.

Guided inquiry: refers to a form of inquiry-based learning in which students' investigations are supported by instructional scaffolds such as guiding questions, prompts, structured worksheets, feedback, and teacher facilitation.

Technology-enhanced learning: refers to the use of digital tools to support teaching and learning processes. In this study, it the use of interactive digital resources to visualize abstract genetic processes and support inquiry-based investigations.

Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL): refers to an instructional approach that integrates guided inquiry pedagogy with educational technology as an essential component of the inquiry process.

Conceptual understanding test: is the researcher-developed or adapted diagnostic instrument used to assess students' understanding and misconceptions about genetics. It consists of multiple-choice item with reasoning components (two-tier), administered as both pre-test and post-test to the groups.

Design-Based Research (DBR): is a methodological approach that involves iterative cycles of designing, implementing, analyzing, and refining educational interventions in real-world settings. In this study, DBR was used to develop, test, and improve the TE-GIBL intervention while generating context-sensitive design principles for effective genetics instruction.

Pre-test: is a genetics conceptual understanding test administered before the intervention to assess students' prior knowledge and misconceptions.

Post-test: is the same or an equivalent test administered after the intervention to measure changes in conceptual understanding attributable to instruction.

2. LITERATURE REVIEW

2.1 Science Education

Science education encompasses the systematic process by which learners develop scientific knowledge, practices, reasoning skills, and dispositions through formal and informal educational experiences. It is concerned not only with the transmission of scientific content but also with enabling students to engage in the ways of thinking and doing that characterize scientific inquiry. Internationally, science education has been guided by reform frameworks that emphasize the integration of disciplinary core ideas, crosscutting concepts, and science and engineering practices as interconnected dimensions of learning (NGSS Lead States, 2013; NRC, 2012). These frameworks reflect a consensus that meaningful science education requires students to engage with ideas deeply, to reason from evidence, and to apply their understanding in varied and authentic contexts.

Historically, science education was dominated by transmission-oriented models in which teachers delivered scientific facts and procedures to largely passive students (Duncan et al., 2009). This model, rooted in a view of science as a fixed body of knowledge, prioritized coverage of content over the development of conceptual understanding and scientific reasoning (Singer & Smith, 2013). Over the past several decades, however, there has been a significant shift toward constructivist and inquiry-oriented approaches that recognize students as active builders of knowledge who bring prior conceptions, experiences, and reasoning frameworks into the classroom (NRC, 2000). This shift has been informed by extensive research in cognitive science, science education, and curriculum theory, and has reshaped both policy and classroom practice in many educational systems worldwide (NRC, 2012).

A central concern in science education research and practice is the relationship between content knowledge and scientific practices. Studies consistently show that students who engage in authentic inquiry, including asking questions, designing investigations, analyzing data, constructing explanations, and argumentation, develop more durable and transferable understanding than those exposed to lecture-based or rote-learning approaches (Minner et al., 2010; NRC, 2012). These practices are not merely procedural but are deeply epistemic: they shape how students understand the nature of scientific knowledge and develop the capacity to evaluate evidence and revise their ideas in light of new information (Duncan et al., 2009).

Science education also grapples with persistent challenges related to equity, access, and student motivation. Research indicates that many students, particularly those from underserved communities or resource-limited educational environments, lack access to quality science instruction, laboratory experiences, and technology-enhanced learning tools (Lara-alecio et al., 2018). In such contexts, students often receive instruction that prioritizes examination preparation over deep conceptual engagement, which may contribute to fragmented knowledge, low motivation, and persistent misconceptions. Addressing these challenges requires not only instructional innovation but also systemic support for teachers, curricula, and learning environments.

In the Ethiopian context, secondary science education faces considerable challenges related to large class sizes, limited laboratory resources, teacher preparation, and curriculum alignment (Chengere et al., 2025). The national curriculum emphasizes scientific knowledge and inquiry but implementation in classrooms is often constrained by structural and resource-related barriers (Santosa & Ratih, 2024). These conditions make it particularly important to explore instructional approaches, such as technology-enhanced guided inquiry, that are both pedagogically effective and adaptable to resource-constrained settings (Lara-alecio et al., 2018). Understanding the broader landscape of science education provides essential context for examining specific challenges and opportunities within biology education and genetics instruction, which are the focus of this study.

2.2 Biology Education

Biology education is a central domain within science education that focuses on developing students' understanding of living systems, their structures, functions, interactions, and underlying molecular and cellular mechanisms (Tsui, C. Y., y Treagust, 2005). As a discipline, biology spans multiple levels of organization from molecules and cells to organisms, populations, and ecosystems and demands that student's reason across these levels to construct coherent explanations of biological phenomena (Knippels et al., 2005; Tsui, C. Y., y Treagust, 2005). This multilevel nature of biology makes it both intellectually rich and pedagogically challenging, as students must integrate knowledge from different domains and use abstract representations to make sense of processes that are largely invisible to the naked eye (Gobert et al., 2011).

At the secondary school level, biology curricula typically introduce students to foundational topics including cell biology, genetics and heredity, evolution, ecology, and physiology. Research consistently shows that students encounter significant difficulties in these areas, often developing persistent misconceptions that interfere with the development of accurate and coherent biological understanding (Banet & Ayuso, 2000; Chattopadhyay, 2005). These difficulties are compounded by the abstract nature of many biological concepts, the heavy reliance on symbolic and diagrammatic representations, and the tendency for traditional instruction to emphasize memorization of terminology and procedures rather than conceptual integration and reasoning (Gobert et al., 2011).

One of the defining characteristics of biology as a school subject is the need for students to reason across multiple levels of biological organization. For example, understanding how a trait is expressed in an organism requires connecting molecular-level processes, such as gene expression and protein synthesis, to cellular-level events, such as mitosis and meiosis, and then to organism-level outcomes, such as phenotypic variation. Research on biology learning has shown that students frequently struggle to make these cross-level connections, often treating knowledge at different levels as separate and unrelated (Duncan & Reiser, 2007; Knippels et al., 2005). This fragmentation of biological knowledge is a major obstacle to deep conceptual understanding and a key challenge for biology educators and curriculum developers.

The role of models and representations in biology education is another prominent area of research. Because biological processes occur at scales and speeds that are inaccessible to direct observation, biology instruction relies heavily on diagrams, animations, three-dimensional models, and computer simulations to make abstract processes visible and manipulable. Research has demonstrated that when students actively engage with these representations, interpreting them, constructing their own, and using them to explain phenomena, their conceptual understanding improves significantly compared to passive exposure (Rutten et al., 2012; Smetana & Bell, 2014). However, the effectiveness of representational tools depends critically on the quality of instructional support and the degree to which students are guided to connect representations to underlying concepts and mechanisms.

Biology education has also been significantly influenced by the rise of molecular and genomic biology, which has expanded the content demands of the discipline and introduced new conceptual challenges (Duncan et al., 2009). Topics such as DNA structure and function, gene expression, genetic engineering, and inheritance at the molecular level are now standard components of secondary biology curricula in many countries, including Ethiopia (FDRE MoE, 2023). These topics require students to reason about entities and processes that are not only invisible but also fundamentally different in kind from the macroscopic phenomena they are more familiar with (Duncan et al., 2009). Helping students develop coherent understanding of these molecular-level concepts, and connect them to their prior knowledge of cells, organisms, and inheritance, is a central challenge in contemporary biology education (Knippels et al., 2005).

In summary, biology education is characterized by the need for multilevel reasoning, the heavy use of abstract representations, and the challenge of helping students overcome persistent misconceptions (Knippels et al., 2005; Tsui, C. Y., y Treagust, 2005). These features make biology education both a demanding and a rewarding field for instructional innovation. The specific challenges associated with genetics, which sits at the intersection of molecular, cellular, and organismal biology, are examined in detail in the following sections. This overview of biology education provides essential background for understanding why technology-enhanced guided inquiry-based learning holds particular promise for supporting conceptual understanding in genetics instruction (Smetana & Bell, 2014).

2.3 Conceptual Understanding in Science Education

Conceptual understanding, in science education refers to students' ability to grasp the underlying ideas, relationships, and explanatory frameworks of a domain. It involves organizing knowledge and using it to explain phenomena, make predictions, solve new problems, and justify claims with appropriate reasoning (Duncan et al., 2009; Singer & Smith, 2013). By its emphasis on coherence, depth, and transfer, where students can flexibly apply their knowledge in varied contexts rather than reproducing definitions or algorithmic steps conceptual understanding is distinguished from surface level learning.

Studies on learning progression and conceptual changes suggested that students rarely move from naïve to expert understanding in a single step instead their idea develop gradually through intermediate level of sophistication (Duncan et al., 2009). Learning progression describe hypothesized path ways along which students' conception become more integrated, mechanistic, and abstract over time, provided that instruction is carefully sequenced and revisits core ideas across grades. Having this conceptual understanding in science education is not having more information, but reorganizing and refining prior knowledge so that it aligns more closely with scientific models and enables explanatory and predictive reasoning.

Studies across different science domain subjects like biology, chemistry and physics show that students' knowledge is usually fragmented, often unable to connect them in to a coherent conceptual frame work (Gobert et al., 2011; Smith et al., 2008). When memorization of vocabulary and procedure is instructed, students perform acceptably on routine task yet still lack robust conceptual understanding like difficulties in applying ideas in new situations, explaining mechanisms, or interpreting representations (Dauer et al., 2019; Pollock, 2009).

In biology education conceptual understanding is important because many core ideas like cellular processes, molecular interactions, and system-level functions cannot be directly observed and must be represented through models, diagrams, and symbolic notations. Researches emphasized that student's need to corporate multiple presentation and reasons across different levels of biological organization (Tsui, C. Y., y Treagust, 2005). When students relate these levels and use them to construct explanations, they are said to possess deeper conceptual understanding; when they cannot, their knowledge remains piecemeal.

In the context of genetics conceptual understanding requires learners to integrate at least three interrelated conceptual models a genetic model, a meiotic model, and a molecular model and to use these models to explain patterns of inheritance and genetic phenomena (Cartier et al., 2006; Duncan et al., 2009). Because of its abstractness, genetics has become a core testing method for studying conceptual understanding and for designing instruction that supports students in moving from fragmented ideas toward coherent, model-based reasoning.

Having such perspectives, this study adopts the view of conceptual understanding as students' ability to organize and use core ideas in genetics in coherent way rather than solely focusing on correct answers in written exams.

2.4 Students' Conceptual Difficulties and Misconceptions in Genetics

Genetics is consistently identified as one of the most difficult topics in secondary biology education due to its abstract nature, symbolic representations, and the need for multilevel reasoning. Different studies report that students develop persistent misconceptions in genetics that remain resistant to instruction, even after completing formal coursework (Chattopadhyay, 2005; Ojo, 2024; Santosa & Ratih, 2024). Another study indicates that many learners face difficult to understand the basics of Mendelian inheritance and particulate nature of genes (Stewart, 1982). Students often treat inheritance as vague and mixed process and only focus on visible traits without considering discrete units. These difficulties emerge at lower secondary levels and most of the time remains unresolved at upper grades.

The most misunderstandings occur in the area of the relationships among genes, chromosomes, cells, and traits. Clough & Wood-Robinson, (1985) showed learners' always confuse things like genes are located only in some parts of the body, or fail to recognize that all somatic cells of an individual contain essentially the same genetic information. Another study confirmed that secondary school students often cannot coherently link molecular structure (DNA), informational units (genes) and higher level structures (chromosomes) (Cisterna et al., 2013; Tsui, C. Y., y Treagust, 2005).

Misconceptions also appear in students' understanding of Mendelian inheritance and dominance. Stewart, (1982) reported that high school students struggle with segregation and independent assortment, often interpreting Punnett squares as mere calculation devices rather than representations of gamete combinations. Tsui, C. Y., y Treagust, (2005) found that learners commonly believe dominant alleles are stronger, larger or more frequent in population, and recessive alleles are necessarily rare or extreme. Duncan & Reiser, (2007) indicated that students have particular difficulty reasoning across ontologically distinct levels linking allele combinations to meiotic events and then to phenotypic outcomes so they tend to memorize patterns like 3:1 ratios without understanding the underlying mechanisms. Duncan et al., (2009) further demonstrated that many students do not progress spontaneously from simple pattern recognition to systematic reasoning about genes, protein, and traits; rather they, remain at levels where inheritance is explained in phenomenological terms.

Current researches has highlighted that misconceptions in genetics are not just random errors but stable, high-confidence alternative frameworks. Using a Certainty of Response Index (CRI) approach, Gusmalini et al., (2020) found that students who select incorrect options while expressing high confidence in their answers, indicating misconceptions rather than lack of knowledge. They reported frequent misunderstandings about gene location, allele interactions, and the meaning of genotype and phenotype. Machová & Ehler,(2023) also documented misconceptions related to meiosis, recombination, and inheritance patterns and showed that these ideas can persist even among students who perform relatively well on traditional tests.

Studies that examine cells and heredity across different grade levels suggest that misconceptions are part of broader conceptual patterns. Cisterna et al., (2013) showed that fifth and seventh grade students most of the time, fail to integrate ideas about cells, chromosomes, and genes, and that some of these early misunderstandings reappear later when students encounter formal genetics. In secondary school, Banet & Ayuso, (2000) reported many learners do not distinguish clearly between somatic and gametic cells, or between mitosis and meiosis, leading to incorrect explanations of how hereditary information is transmitted across generations. Knippels et al., (2005) argued that students' jumping between levels without clear guidance moving from organism to gene and back without understanding intermediate cellular processes contributes to persistent confusion.

Researchers have linked these misconceptions to different instructional and curricular factors. Genetics is often taught through dense terminology, abstract diagrams, and algorithmic problem solving, with limited use of models and representations that explicitly connect molecular, cellular, and organismal levels (Banet & Ayuso, 2000; Stewart, 1982; Tsui, C. Y., y Treagust, 2005). Teacher-centered lecturing and textbook-driven instruction encourage memorization of rules without opportunities for students to test ideas, confront inconsistencies, or reason about mechanisms (Kılıç Mocan, 2021; Knippels et al., 2005).

Studies further suggest that traditional instructional approaches also play a role to the persistence of these misconceptions. Teacher-centered instruction often focuses on symbolic manipulation (e.g., Punnett squares) without sufficient emphasis on causal mechanisms and conceptual explanation. As a result, students may achieve correct answers while holding incorrect underlying conceptions, making misconceptions difficult to detect and correct through assessment (Santosa & Ratih, 2024).

Recent research indicates that guided inquiry and visualization tools can play a significant role in addressing genetics misconceptions. Inquiry-based activities encourage students to ask questions, generate explanations, and use evidence to evaluate their ideas, while simulations and interactive tools support visualization of abstract processes such as meiosis and inheritance patterns. However, their effectiveness depends on the presence of structured guidance that helps students coordinate evidence with explanations and avoid superficial exploration (R. L. Bell et al., 2017; Deep et al., 2020; Lazonder & Harmsen, 2016).

In summary, misconceptions in genetics are widespread, conceptually structured, and resistant to change. They cluster around key ideas such as the nature and location of genes, the relationships among DNA, genes, chromosomes, and cells, the mechanisms of meiosis and fertilization, and the meaning of dominance and recessiveness (Clough & Wood-Robinson, 1985; Duncan & Reiser, 2007; Gusmalini et al., 2020; Machová & Ehler, 2023, 2023; Stewart, 1982; Tsui, C. Y., y Treagust, 2005). These challenges highlight the need for instructional designs that integrate guided inquiry, conceptual scaffolding, and technology-enhanced visualization to support meaningful learning and conceptual change in genetics education. The present study responds to this need by examining whether a Technology-Enhanced Guided Inquiry-Based Learning can help Grade 11 students in Ethiopia overcome such misconceptions and develop more coherent understandings of genetics.

2.5 Traditional (Teacher-Centered) Approaches in Biology Teaching

Traditional or teacher-centered approaches have long dominated biology instruction at the secondary school level. These approaches are characterized by teacher-led explanations, lecture-based delivery, note copying, textbook-centered instruction, and routine end-of-chapter exercises. In such classrooms, the teacher is the primary source of knowledge, while students are largely passive recipients of information. Research suggests that teacher-centered methods may facilitate efficient content coverage but they often limit opportunities for deep learning and conceptual understanding, particularly in complex scientific domains such as genetics (Santosa & Ratih, 2024).

In traditional biology classrooms, learning activities frequently emphasize memorization of facts and definitions rather than conceptual integration and scientific reasoning. Students are often assessed through recall-based tests and procedural tasks, which may encourage surface learning strategies. In genetics instruction, this approach commonly overreliance on symbolic problem-solving techniques, such as Punnett square calculations, without adequate attention to the underlying biological mechanisms that explain inheritance patterns (Chattopadhyay, 2005; Santosa & Ratih, 2024). As a result, students may achieve correct answers while holding incorrect or incomplete conceptual understandings.

Teacher-centered instruction often provides limited opportunities for students to engage in essential scientific practices, such as asking questions, designing investigations, interpreting evidence, and constructing explanations. These practices are essential to meaningful science learning and conceptual change; however, they are frequently marginalized in classrooms where instructional time is dominated by teacher explanation and rote repetition (NRC, 2000). Research has consistently shown that when students are not actively involved in scientific practices, their understanding of scientific concepts tends to remain fragmented and vulnerable to persistent misconceptions (Herrmann et al, 2025; Pacaci, 2024). Consequently, instructional approaches that fail to engage learners in authentic scientific practices may hinder deep conceptual understanding and long-term knowledge construction.

Another limitation of traditional teaching method is their inadequate support for visualizing abstract biological processes. Genetics involves processes that cannot be directly observed, such as chromosome behavior during meiosis and molecular interactions underlying gene expression. Traditional instruction often relies on static textbook diagrams and verbal explanations, which may be insufficient for helping students, develop accurate mental models of these processes. Studies suggest that lack of visualization contributes significantly to students' difficulties and misconceptions in genetics (R. L. Bell et al., 2017).

Teacher-centered approaches are also influenced by contextual constraints such as large class sizes, limited instructional time, and pressure to complete the syllabus. Under these conditions, teachers may prioritize efficient delivery of content over exploratory or inquiry-oriented activities, even though the pedagogy values student-centered approaches. Research has shown that such systemic constraints can discourage innovation in teaching practices and reinforce reliance on traditional methods (Santosa & Ratih, 2024).

Comparisons between traditional instruction and student-centered approaches further indicate that teacher-centered methods are generally less effective in promoting higher-order learning outcomes, including conceptual understanding, reasoning, and transfer of knowledge. Studies comparing inquiry-based and traditional approaches consistently report greater learning gains and engagement for students exposed to inquiry-oriented instruction, particularly when guidance and scaffolding are provided (Lazonder & Harmsen, 2016).

Despite of having these limitations, traditional teaching methods continue to be widely used in secondary biology classrooms. This persistence usage underscores the need for instructional models that are both pedagogically effective and practically feasible within existing school contexts. Integrating guided inquiry with supportive technologies offers a promising alternative that can address the shortcomings of traditional instruction while remaining adaptable to classroom realities.

To conclude with traditional teacher-centered approaches in biology teaching often emphasize content transmission and procedural practice rather than conceptual understanding and scientific reasoning. These limitations are particularly seen in genetics education, where complex and abstract concepts demand instructional strategies that actively engage students in inquiry, visualization, and explanation-building.

2.6 Inquiry-Based Learning (IBL)

Inquiry-based learning (IBL) is a learner-centered instructional approach in which students construct scientific knowledge by posing questions, collecting and interpreting evidence, and developing and justifying explanations. Rather than receiving ready-made facts, learners actively engage in processes such as probing, searching, exploring, and investigating authentic problem In science education IBL often described as guided discovery, where teachers support students' inquiry where they can reach at scientifically acceptable explanation through their own investigation (Lord, 2010)**.** Based on this frame work students analyze their result and reach a conclusion in order to answer research questions, mirroring the aspect scientific practice (R. L. Bell et al., 2017).

The NRC (2000) outlined five core characteristics of inquiry-based science teaching: learners (a) engage with scientifically oriented questions, (b) give priority to evidence in responding to these questions, (c) formulate explanations from evidence, (d) evaluate their explanations in light of alternative explanations and established scientific knowledge, and (e) communicate and justify their explanations to others. These characteristics emphasize that inquiry is not only a set of hands-on activities but also a reasoning-rich process in which students coordinate theory and evidence, critique ideas, and refine their understanding over time (NRC, 2000). Such practices are particularly important for domains like genetics, where abstract entities (e.g., genes, alleles, chromosomes) and multi-level mechanisms must be inferred from indirect evidence.

IBL can be implemented at different levels based on the amount of structure and guidance provided by the teacher. R. Bell, (2005) describe four levels of inquiry: confirmation, structured, guided, and open inquiry. In confirmation inquiry, students verify a known principle using a given procedure; in structured inquiry, they investigate a question posed by the teacher using a prescribed method. Guided inquiry requires students to design procedures to answer a teacher-posed question, whereas in open inquiry learners generate their own questions, design investigations, and interpret results (R. Bell, 2005; Bianchini & Colburn, 2000). For secondary-school contexts, guided inquiry is often considered pedagogically appropriate because it balances student autonomy with necessary support for dealing with complex content and procedures (R. Bell, 2005; Bianchini & Colburn, 2000).

From the perspective of pedagogy inquiry learning has been conceptualized as a complex scientific process composed of smaller, logically connected inquiry phases. Pedaste et al., (2015) define these phases as orientation, conceptualization (questioning and hypothesis generation), investigation (exploration and experimentation), conclusion, and discussion, which together form the inquiry cycle. The idea is that learners construct their own knowledge by replicating, in simplified form, the path that scientists follow, while also developing an understanding of how and why scientists think in particular ways during inquiry (Dobber et al., 2017; Pedaste et al., 2015).

Many empirical researches indicate that IBL can positively influence students’ science process skills, achievement, and attitudes when appropriately scaffolded. They have shown that inquiry-based science learning can significantly improve students’ laboratory and science process skills, their ability to remember course content, and their attitudes towards science and scientific activities, often outperforming traditional lecture-based methods (Aktamiş & Hİğde, 2016; Duncan & Reiser, 2007; Erg et al., 2011; Hmelo-silver et al., 2007). Meta-analytic work similarly suggests that inquiry-based teaching is generally more effective than traditional instruction for fostering conceptual understanding, provided that learners receive sufficient guidance during the inquiry process (Lazonder & Harmsen, 2016b; Minner et al., 2010).

In the context of genetics education, IBL offers several specific advantages. First, it provides opportunities for students to confront and reorganize their prior conceptions by designing and conducting investigations, analyzing patterns in data (e.g., monohybrid and dihybrid crosses), and testing predictions derived from inheritance models. Second, inquiry-oriented tasks require students to reason hypothetico-deductively and to coordinate explanations across different biological levels (molecular, cellular, organismal level), which are critical demands in modern genetics learning (Baker & Lawson, 2001; Duncan & Reiser, 2007; Knippels et al., 2005). Third, by engaging students in authentic problem-solving and argumentation, IBL can promote more positive attitudes and stronger motivation towards learning challenging topics such as meiosis, gene expression, and probability in inheritance (Gibson & Chase, 2002).

At the same time, inquiry-based environments may impose high cognitive and procedural demands on learners, especially when dealing with abstract domains like genetics. Unguided or minimally guided inquiry has been criticized for overloading students' working memory and leading to inefficient or superficial learning(De Jong, 2006; Kremer et al., n.d.). Recent reviews therefore emphasize that effective IBL in science should include structured scaffolds such as prompts, worked examples, visual representations, and step-wise guidance—that gradually fade as students gain expertise (Lazonder & Harmsen, 2016b; Mulder et al., 2014). This study responds to these insights by employing a guided-inquiry approach in which IBL is systematically supported and complemented by computer simulations, with the aim of enhancing Grade 11 students' conceptual understanding of genetics and reducing persistent misconceptions.

2.7 Guided Inquiry-Based Learning

Guided Inquiry-Based Learning (GIBL) is an instructional approach that combines the learner-centered principles of inquiry-based learning with structured instructional support. In guided inquiry, students actively engage in scientific inquiry processes such as questioning, investigating, analyzing evidence, and constructing explanations while receiving explicit guidance through prompts, scaffolds, feedback, and teacher facilitation. This balance between student autonomy and instructional support is particularly important in complex scientific domains where learners may struggle to regulate their own inquiry processes (Lazonder & Harmsen, 2016).

Research strongly supports the effectiveness of guided inquiry over minimally guided or unguided inquiry. A comprehensive meta-analysis by Lazonder & Harmsen, (2016) demonstrated that inquiry learning with guidance yields significantly higher learning outcomes than inquiry without guidance, especially for students with limited prior knowledge and in conceptually demanding topics. Guidance helps learners focus on relevant variables, interpret data meaningfully, and link evidence to scientific explanations, thereby reducing cognitive overload and unproductive exploration.

In secondary science education, guided inquiry has been shown to enhance students' conceptual understanding, reasoning skills, and engagement. By providing structured inquiry phases like orientation, hypothesis generation, investigation, explanation, and reflection, guided inquiry enables students to experience authentic scientific practices while maintaining clarity and direction in learning tasks (Santosa & Ratih, 2024). This structure is especially beneficial in biology topics like genetics, where students must coordinate multiple representations and abstract ideas.

Guided inquiry also supports conceptual change, as it encourages students to articulate prior conceptions, test them against evidence, and revise their understanding through structured reflection. Research suggests that such guided processes are necessary for addressing persistent misconceptions, which are unlikely to be corrected through direct instruction alone (Chattopadhyay, 2005). Teacher guidance plays a critical role in facilitating productive cognitive conflict and supporting students in reconstructing their knowledge.

The role of the teacher in guided inquiry is fundamentally different from that in traditional instruction. Rather than acting as the sole source of knowledge, the teacher functions as a facilitator who designs inquiry tasks, poses strategic questions, provides timely feedback, and scaffolds students' reasoning. This role requires careful planning and pedagogical skill, as guidance must be adaptive and responsive to students' needs without removing opportunities for independent thinking (Lazonder & Harmsen, 2016).

Despite its advantages, guided inquiry can be challenging to implement consistently due to time constraints, classroom management demands, and teachers' familiarity with inquiry pedagogy. In biology education, inadequate instructional materials and limited teacher preparation are frequently reported barriers to effective guided inquiry implementation, particularly in resource-limited settings (Chengere, 2025). Research has also documented that students in guided inquiry biology classrooms encounter procedural and cognitive challenges that require structured scaffolding and well-designed tasks to be overcome (Castro & Morales, 2017).

Furthermore, systematic reviews of biology lab instruction emphasize that although guided inquiry promotes learning gains and more expert-like scientific thinking, variability in assessment practices and institutional support can limit its broad adoption (Beck et al., 2014). However, when supported by targeted materials, professional development, and alignment with curriculum goals, guided inquiry has been shown to positively influence both student attitudes and teacher engagement in biology instruction (Abza, 2022).

In summary, guided inquiry-based learning provides a theoretically and empirically supported approach for promoting meaningful science learning. By combining active student engagement with structured instructional support, guided inquiry addresses the limitations of both traditional teaching and unguided inquiry. This approach forms a critical pedagogical foundation for integrating educational technology into inquiry-based science instruction, as discussed in the subsequent section.

2.8 Technology-Enhanced Learning in Science Education

Technology-Enhanced Learning (TEL) refers to the purposeful integration of digital tools and resources to support teaching and learning processes. In science education, TEL has gained increasing attention because of its potential to support visualization, interactivity, and inquiry experiences that are difficult to achieve through traditional instructional methods alone. Digital technologies such as computer simulations, animations, virtual laboratories, and web-based inquiry environments can provide learners with opportunities to explore scientific phenomena dynamically and to engage in higher-order thinking processes (Rutten et al., 2012; Smetana & Bell, 2014).

One of the primary advantages of technology-enhanced learning in science is its capacity to make abstract and invisible processes visible. Many scientific concepts, particularly in biology, involve processes that cannot be directly observed, such as molecular interactions, cellular mechanisms, and genetic processes. Simulations and interactive visualizations allow students to manipulate variables, observe outcomes, and test hypotheses in ways that support conceptual understanding and model-based reasoning (Smetana & Bell, 2014). This feature is especially valuable in genetics education, where students often struggle to visualize meiosis, inheritance patterns, and probabilistic outcomes.

A research indicates that technology-enhanced instruction can positively influence students' conceptual understanding, engagement, and motivation when digital tools are aligned with learning objectives. Meta-analyses and review studies show that simulations and interactive environments can lead to improved learning outcomes compared with static representations, particularly when students are actively engaged in exploration and reflection (Deep et al., 2020; Rutten et al., 2012). Technology also supports differentiated learning by allowing students to progress at their own speed and revisit complex ideas as needed.

However, research also cautions that technology alone does not guarantee effective learning. Simply introducing digital tools into the classroom without pedagogical integration may result in superficial engagement or cognitive overload. Students may focus on manipulating the technology rather than understanding the underlying scientific concepts, especially when guidance is limited (Smetana & Bell, 2014). This finding indicates the importance of instructional design and teacher mediation in technology-enhanced learning environments.

Studies further suggest that the effectiveness of TEL depends on the pedagogical role assigned to technology. When digital tools are used as add-ons or demonstrations controlled solely by the teacher, their impact on learning are often limited. In contrast, when technology functions as a cognitive tool supporting inquiry, reasoning, and explanation, it can enhance learning outcomes (Deep et al., 2020). This perspective aligns with constructivist and sociocultural theories, which emphasize the role of tools in mediating cognitive activity.

In resource-constrained educational contexts, technology-enhanced learning also offers practical advantages. Freely available simulations and web-based tools can supplement limited laboratory resources and provide students with inquiry experiences that would otherwise be inaccessible. Research indicates that even low-cost technological integration, when pedagogically structured, can contribute meaningfully to science learning (Lara-alecio et al., 2018).

Overall, technology-enhanced learning brings significant promise for improving science education by supporting visualization, inquiry, and conceptual integration. However, its effectiveness depends critically on how technology is embedded within instructional approaches. This insight highlights the need for integrating technology within guided inquiry frameworks, rather than treating it as an isolated instructional component. Such integration is particularly relevant for addressing conceptual challenges in genetics education and forms the foundation for the Technology-Enhanced Guided Inquiry-Based Learning approach.

2.9 Technology-Enhanced Guided Inquiry-Based Learning

Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) is an instructional approach that integrates the pedagogical principles of guided inquiry with the affordances of educational technology to support meaningful learning in complex scientific domains. Rather than treating technology and inquiry as separate instructional components, TE-GIBL embeds digital tools particularly simulations and interactive environments directly within the inquiry process as cognitive and pedagogical scaffolds (Deep et al., 2020; Smetana & Bell, 2014).

The theoretical foundation of TE-GIBL is grounded in constructivist learning theory, which emphasizes that learners actively construct knowledge through interaction with ideas, tools, and social contexts. Guided inquiry provides the pedagogical structure necessary to support this process, while technology mediates learners’ interactions with abstract concepts and supports exploration, visualization, and reflection. Research indicates that this combination is particularly effective for topics that are conceptually demanding and difficult to observe directly, such as genetics (Lazonder & Harmsen, 2016; Smetana & Bell, 2014).

Studies demonstrate that technology-enhanced inquiry environments can improve students’ conceptual understanding, reasoning skills, and engagement when appropriate guidance is provided. For example, simulations allow students to manipulate variables, observe dynamic processes, and test hypotheses, while guided inquiry structures help learners focus on relevant features, interpret outcomes, and connect evidence to scientific explanations (Deep et al., 2020; Rutten et al., 2012). Without guidance, students may explore simulations superficially or misinterpret results; therefore, teacher scaffolding and structured tasks are essential components of effective TE-GIBL.

In genetics education, TE-GIBL offers particular advantages. Genetic processes such as meiosis, segregation, independent assortment, and inheritance patterns are abstract and temporally dynamic, making them difficult to understand through static representations alone. Simulations can visualize these processes and allow repeated exploration, while guided inquiry activities encourage students to generate questions, predict outcomes, analyze patterns, and revise explanations. Research suggests that such integrated approaches help reduce misconceptions and support conceptual change more effectively than traditional instruction or technology use alone (Chattopadhyay, 2005; Santosa & Ratih, 2024).

TE-GIBL also aligns with evidence from meta-analyses indicating that guided inquiry produces stronger learning outcomes than unguided inquiry, particularly when combined with instructional supports such as prompts, feedback, and structured reflection (Lazonder & Harmsen, 2016). Technology can enhance these supports by providing immediate feedback, interactive representations, and opportunities for self-paced exploration. However, the design of TE-GIBL environments must be intentional, ensuring that technological tools are aligned with learning goals and inquiry phases rather than serving as distractions or isolated demonstrations.

Despite its potential, research highlights that the effectiveness of TE-GIBL depends on careful instructional design and contextual adaptation. Classroom constraints such as limited time, access to technology, and teachers' familiarity with inquiry pedagogy can influence implementation quality. Therefore, TE-GIBL interventions must be designed flexibly and refined through empirical evidence gathered in real classroom settings (Lara-alecio et al., 2018).

In summary, Technology-Enhanced Guided Inquiry-Based Learning represents a promising instructional approach that combines the strengths of guided inquiry and educational technology. By embedding simulations and interactive tools within structured inquiry processes, TE-GIBL addresses the limitations of both traditional instruction and unguided inquiry. This integrated approach is particularly well suited for supporting conceptual understanding in genetics.

2.10 Theoretical Framework

This study is grounded in a combination of constructivist and conceptual-change perspectives, inquiry-based learning theory, and theories of learning with computer simulations and multimedia environments (Gertzog, 1982; Hmelo-silver et al., 2007; Wang & Hannafin, 2005). Together, these perspectives explain why an inquiry-based approach integrated with computer simulations is expected to enhance students' conceptual understanding of genetics and reduce misconceptions.

Constructivism and conceptual change in genetics learning

From a constructivist perspective, students actively construct their own understanding of scientific concepts based on prior knowledge, everyday experiences, and classroom instruction. Learning is viewed not as the simple accumulation of facts, but as the reorganization and refinement of existing mental models (Duncan et al., 2009; Tsui, C. Y., y Treagust, 2005). In genetics, a number of studies show that learners enter instruction with strong, often coherent alternative conceptions such as viewing genes as bits of traits, confusing genes and chromosomes, overgeneralizing dominance, or believing that acquired characteristics can be inherited (Clough & Wood-Robinson, 1985; Kılıç Mocan, 2021; Machová & Ehler, 2023; Stewart, 1982; Tsui, C. Y., y Treagust, 2005).

Conceptual-change views argue that for meaningful learning to occur, instruction must **elicit these prior conceptions**, create cognitive conflict or dissatisfaction with them, and offer scientifically more adequate explanations that are intelligible, plausible, and fruitful for the learner (Duncan et al., 2009; Tsui, C. Y., y Treagust, 2005). Diagnostic tools such as two-tier or CRI-based tests are therefore essential for identifying misconceptions and monitoring their evolution (Gusmalini et al., 2020). This study adopts this stance by explicitly assessing students' conceptual understanding and misconceptions before and after instruction, and by designing learning activities that confront and restructure problematic ideas about core genetics concepts.

Learning progressions and multilevel reasoning in genetics

Duncan et al., (2009), propose a **learning progression for modern genetics** in which students move from phenomenological descriptions of inheritance toward increasingly mechanistic explanations that integrate molecular, cellular, and organismal levels. Progress along this route requires students to coordinate three major conceptual models: a genetic (transmission) model, a meiotic model, and a molecular model. Many students, however, remain at intermediate levels where they can manipulate symbols and tables like Punnett squares but do not understand how alleles, DNA sequences, and cellular processes generate observed inheritance patterns (Duncan et al., 2009; Duncan & Reiser, 2007).

This study uses the learning progression framework as a lens for interpreting students' conceptual understanding. The integrated IBL–simulation approach is intended to support movement toward higher levels of the progression by asking students to generate and test explanations that link **observable patterns** like offspring ratios to **underlying mechanisms** like meiosis, segregation, and recombination, as visualized in simulations.

Inquiry-based learning theory

IBL theory conceptualizes learning as an active process in which students engage with scientifically oriented questions, gather and interpret evidence, construct and evaluate explanations, and communicate and justify their (R. Bell, 2005). Pedaste et al., (2015) synthesized existing inquiry models into an **inquiry cycle** comprising orientation, conceptualization, investigation, conclusion, and discussion. In this view, effective inquiry instruction structures classroom activities around these phases and provides scaffolds that help learners move from initial questions to evidence-based explanations.

The present study draws on this framework by designing genetics lessons in the IBL and IBL–simulation conditions so that students: are oriented with engaging genetics problems, formulate questions or tentative explanations, investigate using data (from tasks, simulations, or other materials), draw conclusions about inheritance patterns and mechanisms, and discuss and reflect on their findings.

Guided inquiry is emphasized, consistent with research showing that structured support is necessary to prevent cognitive overload and to ensure that students focus on relevant variables and reasoning processes (de Jong et al., 2019; Lazonder & Harmsen, 2016b).

Technology-Enhanced Learning Theory

Technology-enhanced learning theory highlights the role of digital tools as mediators of cognition and learning (Wang & Hannafin, 2005). From this perspective, technology is not merely a delivery mechanism, but a cognitive tool that can support visualization, exploration, and reasoning (Smetana & Bell, 2014). In science education, simulations and interactive environments enable learners to observe dynamic processes, manipulate variables, and test hypotheses in ways that are not possible through static representations.

Research indicates that technology is most effective when it is pedagogically integrated into learning activities rather than used as an isolated tool. When combined with guided inquiry, simulations can function as scaffolds that reduce cognitive load, support conceptual integration, and facilitate explanation-building (Deep et al., 2020; Rutten et al., 2012). In this study, simulations are embedded within inquiry phases to support students' understanding of abstract genetic processes such as meiosis, inheritance patterns, and probabilistic outcomes.

In summary, the theoretical framework of this study integrates constructivist learning theory, inquiry learning theory, and technology-enhanced learning theory within a design-based research methodology. This integrated framework provides a strong foundation for examining how Technology-Enhanced Guided Inquiry-Based Learning can enhance Grade 11 students’ conceptual understanding of genetics and generate empirically grounded design principles for effective science instruction.

2.11 Conceptual frame work

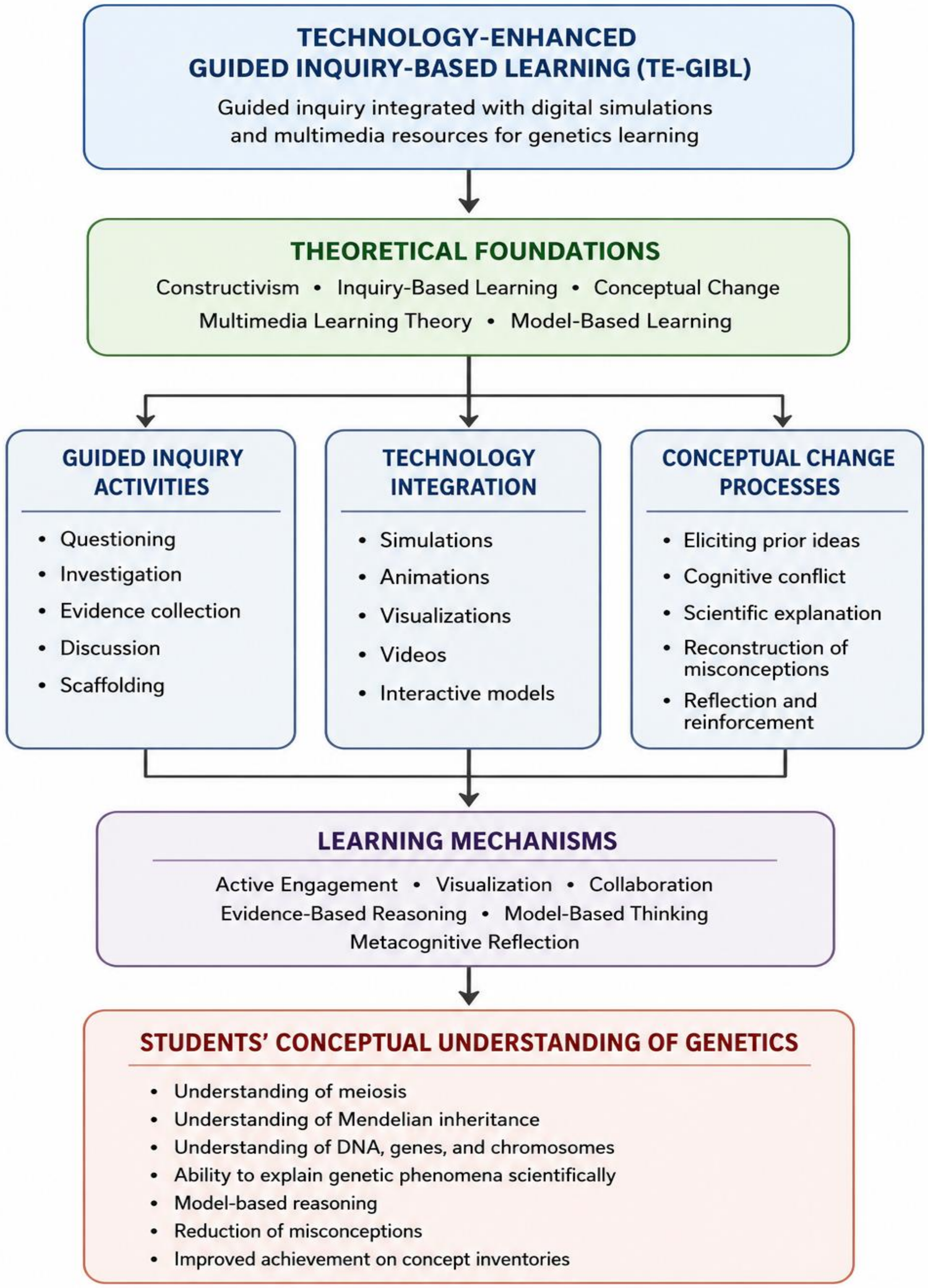

Fig 1: Conceptual framework flowchart on learning genetics through TE-GIBL

3. Research Methodology

3.1 Methodological Framework

3.1.1 Research Paradigm

The research paradigm was pragmatism, because it has emphasized in using multiple methods for investigating the real time misconception in genetics concept in grade 11 students and is trying to address what methodology works best to find the solution. As (Teddlie, 2010) describes pragmatism promotes methodological flexibility and the search for what best works for answering research question.

3.1.2 Research Approach

The research approach followed was a mixed research approach because both quantitative and qualitative evidence were used throughout the study. Quantitative evidence, including pre-test and post-test results, was used to assess changes in students' conceptual understanding and identify areas requiring improvement. Together, these data sources informed iterative refinements of the TE-GIBL intervention across implementation cycles and facilitated a comprehensive interpretation of the findings. Qualitative evidences like observation, student work, and interviews used to support improvements and refinements across the different stages of implementation and help to interpret quantitative test results.

3.1.3 Research Design

This study has employed a design-based research (DBR) methodology to iteratively develop, implement, and refine a Technology-Enhanced Guided Inquiry-Based Learning for enhancing genetics instruction in Fasilo secondary school in Bahir Dar Amhara regional state, Ethiopia.

The research was grounded in constructivist learning theories, emphasizing how students build knowledge through inquiry and visualization tools (De Jong, 2006; de Jong et al., 2021). Close collaboration between the researcher, teachers, and school administrators was involved to co-design and adapt the intervention, drawing on multiple forms of evidence to uncover mechanisms of learning and implementation challenges. The process was unfolded across different iterative cycles, each building on the previous to refine the instructional approach:

3.2 Description of the Study Area and Participants

The study was conducted in Bahir Dar City, the administrative capital of the Amhara National Regional State, located in northwestern Ethiopia. Geographically, Bahir Dar City is situated at approximately 11.59° North latitude and 37.39° East longitude, with an average elevation of about 1,800 meters above sea level. Specifically, the study was conducted at Fasilo Secondary and Preparatory School, a government-owned secondary school administered by the Bahir Dar City Education Office.

The participants of study were Grade 11th D students enrolled in the natural science stream.

3.3 Sampling Technique and Sample Size

This study employed a multi-stage non-probability sampling technique under natural school conditions. At the first stage, Fasilo Secondary School was selected purposively from secondary schools in Bahir Dar City because it met the following criteria: (a) implementation of the Ethiopian national curriculum, (b) provision of Grade 11 natural science classes, (c) availability of basic ICT facilities, including a computer laboratory and reliable electricity, and (d) administrative willingness to support the implementation of the intervention. These criteria were necessary to ensure the feasibility of implementing and monitoring the Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) intervention, consistent with similar school-based studies conducted under existing infrastructural conditions (Baidoo & Ekem-ferguson, 2025; Geban et al., 1992; Gibbons et al., 2004; Oduro-okyireh & Gyamfi, 2025).

At the second stage, one intact Grade 11 natural science class (Grade 11 D) was selected because reorganizing students into new groups was impractical and could disrupt normal instructional activities. Therefore, all students in the class participated in the study. The sample consisted of 50 students, including 22 females and 28 males.

Although purposive and intact-class sampling facilitated the implementation of the intervention in a natural classroom setting, these techniques may limit the generalizability of the findings to other schools and student populations. Consequently, the results should be interpreted within the context of schools with similar characteristics and resources

3.4 Data Collection Instruments

To answer the research questions and meet the specific objectives multiple data collection instruments were applied like; conceptual understanding and misconception diagnostic test, a classroom observation and checklist and semi-structured (focused group) discussion and interview. These instruments together have provided a complementary qualitative and quantitative data on students' learning outcomes, experiences, and the implementation of the instructional approaches.

3.4.1 Conceptual Understanding and Misconception Diagnostic Test

A researcher-developed genetics conceptual understanding test was used as pre-test and post-test. Multiple-choice questions with distractors targeting common misconceptions, short constructed-response items, and reasoning-based problems requiring explanation items were constructed.

A researcher developed total of 20 two-tier genetics questions were prepared in order to diagnosing misconception and to analyze the conceptual understanding of grade 11^{th} D of Fasilo secondary school students. The prepared questions were multiple-choice questions with distractors targeting common misconceptions, short constructed-response items, and reasoning-based problems requiring explanation items were constructed.

The genetics achievement test was a two-tier diagnostic items that were categorized in to four major genetics concepts:

I. Gene Structure, Function, and Expression
II. Mendelian Genetics and Probability
III. Meiosis, Gametes, and Fertilization
IV. Genetic Variation, Mutation, and Environment

The response from the student were recorded in to three categories

- Score 0 = Both content answer and reason incorrect (misconception)
- Score 1 = Either content answer or reason correct (partial understanding)
- Score 2 = Both content answer and reason correct (full conceptual understanding)

Validity and reliability of the test was assessed. Content validity was established through two approaches. First, the items were drawn directly from the Grade 11 genetics syllabus, thereby ensuring alignment between the test and the content taught during the intervention. Second, the distractors and reasoning options were based on common misconceptions documented in genetics education research; consequently, the instrument was able to capture the misunderstandings that students commonly bring to the classroom.

Reliability analysis was conducted using Cronbach's alpha to determine the internal consistency of the two-tier diagnostic genetics test. The internal consistency of the two-tier diagnostic genetics test was examined using Cronbach's alpha. Table 3.1 presents the reliability statistics for each construct.

Table 3.1 *Reliability Statistics of the Two-Tier Genetics Diagnostic Test*

Construct	Cronbach's Alpha	Interpretation
Conceptual Understanding	.80	Acceptable to Good
Misconceptions	.74	Acceptable

Note. *Alpha values are interpreted as: $\alpha \geq .90$ = Excellent; $.80 \leq \alpha < .90$ = Good; $.70 \leq \alpha < .80$ = Acceptable; $.60 \leq \alpha < .70$ = Questionable (George & Mallery, 2003).*

The reliability analysis indicated that the conceptual understanding items scored a Cronbach's alpha of 0.80, showing good internal consistency, while the misconception items yielded $\alpha = 0.74$, indicating acceptable reliability. Both values exceed the commonly accepted threshold of .70 recommended for research instruments in educational studies. These findings confirm that the instrument was sufficiently reliable for assessing students' conceptual understanding and misconceptions in genetics prior to and after the TE-GIBL intervention.

3.4.2 Classroom Observation Checklist

A structured observation tool was used to examine how each instructional approach was enacted in real classrooms. This was important in DBR, where understanding implementation helps explain learning outcomes.

The checklist has included indicators linked to:

- teacher behaviors (questioning, guidance, linking ideas)
- student behaviors (engagement, group work, use of evidence)
- inquiry phases (orientation, investigation, conclusion, discussion)

Observations during selected lessons had helped to verify that the instructional approaches differ in practice as intended and had provided context for interpreting test and questionnaire results.

The validity of the observation checklist was established through content validation by ensuring that the items were derived from established frameworks for inquiry-based teaching and research on digital inquiry environments. Consequently, the checklist items reflected observable aspects of classroom practice, including teacher guidance, student engagement, and the integration of simulations during instruction. Thus, the instrument was considered appropriate for capturing the essential features of the TE-GIBL implementation. Reliability of the observation checklist was enhanced through repeated observations conducted from the pilot phase onward. These observations enabled the comparison of ratings and helped clarify the interpretation of checklist items, thereby promoting consistency in the recording and evaluation of classroom practices.

3.4.3 Semi-Structured Interviews and Focused Group Discussions

To gain deeper insight into students' thinking especially their misconceptions and how they experienced the learning environments semi-structured interviews and focus group discussion had been conducted with a small purposive sample of students from each group.

Prompts had explored:

- prior ideas and difficulties in genetics
- how the lessons influenced their understanding
- experiences using inquiry tasks and technologies like simulations, video
- perceived challenges and benefits

These data had helped to explain *why* certain misconceptions persisted or changed and were supported the refinement of the intervention for future cycles.

The validity of the interview and discussion guides was established by aligning the prompts with the research objectives and by informing them with findings obtained from the early test and questionnaire data. Furthermore, experts reviewed the guides to ensure that the questions were appropriate, relevant, and clearly phrased. Consequently, the instruments were considered suitable for eliciting information related to students' experiences and perceptions of the intervention.

To enhance reliability, interviews and discussions were systematically documented. In addition, records of participants' responses were maintained to ensure consistency and accuracy in data collection and to provide a dependable basis for subsequent analysis.

3.5 Data Collection Procedures

The data collection process was guided by the iterative logic of Design-Based Research (DBR), which emphasizes conducting research within authentic classroom settings while simultaneously generating evidence for evaluating and refining the intervention. Accordingly, data collection was organized into four interconnected phases: preparation, pre-testing, implementation, and post-implementation. Each phase contributed to understanding not only the effectiveness of the intervention but also the practical conditions under which it was enacted.

3.5.1 Preparation Phase

Following the selection of schools and intact classes, the researcher met with school administrators and biology teachers to explain the purpose of the study, discuss the research schedule, and clarify data collection requirements. In addition, the teacher assigned to the Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) group received a brief orientation on the instructional materials, the sequence of inquiry activities, and the integration of simulations. This preliminary orientation ensured a shared understanding of the instructional procedures and promoted faithful implementation of the lessons.

Furthermore, practical arrangements were finalized in collaboration with the school administration. Lesson schedules, computer laboratory availability, and classroom observation times were carefully coordinated to minimize disruptions to regular school activities and to ensure the smooth execution of the intervention.

3.5.2 Pre-Testing Phase

Before the genetics unit was introduced, students completed the conceptual understanding and misconception diagnostic test under normal classroom conditions. Prior to administration, students were informed that the test was intended solely for research purposes and would not affect their academic grades. Consequently, the pre-test provided baseline information regarding students' initial conceptual understanding and existing misconceptions about genetics.

3.5.3 Implementation Phase

The implementation phase encompassed the actual teaching of the genetics unit and extended over the periods allocated by the Grade 11 biology curriculum. During this stage, the intervention was carried out under authentic classroom conditions in order to preserve the natural context emphasized by DBR.

Throughout the intervention, students engaged in inquiry-based learning tasks facilitated by their teacher and supported by computer-based technologies and simulations.

Meanwhile, teachers maintained their normal classroom management practices so that instruction proceeded as naturally as possible. This approach ensured that the intervention was embedded within everyday teaching practices rather than imposed under artificial conditions.

Simultaneously, classroom observations were conducted to document teacher guidance, students' engagement in inquiry activities, progression through inquiry phases, and the integration of technological tools. These observations provided valuable insights into how the intervention unfolded in practice and helped explain variations in students' learning experiences.

In addition, field notes were recorded continuously throughout the instructional period. These notes captured unexpected events, practical constraints, classroom interactions, and instances in which students' questions or responses revealed changes in their conceptual understanding. Such ongoing documentation represented an essential component of the design aspect of DBR, as it generated evidence for refining and improving the intervention in subsequent cycles.

3.5.4 Post-Implementation Phase

At the conclusion of the genetics unit, the same conceptual understanding and misconception diagnostic test administered during the pre-testing phase was re-administered as a post-test. This allowed the researcher to examine changes in students' conceptual understanding and determine the extent to which misconceptions had been reduced following the intervention.

Moreover, a purposive sample of students from each instructional group participated in semi-structured interviews and small focus group discussions. These sessions provided opportunities for students to reflect on their learning experiences, discuss challenges encountered during the lessons, and describe misconceptions that either persisted or changed throughout the intervention. Particular attention was given to students' experiences with inquiry activities and computer simulations, thereby providing deeper insights into the mechanisms underlying conceptual change.

Finally, teachers were invited to share reflective comments concerning the strengths and challenges of the intervention. They discussed aspects that worked effectively, difficulties encountered during implementation, and modifications they would recommend for future applications. These reflections constituted an important source of feedback and supported the iterative refinement of the Technology-Enhanced Guided Inquiry-Based Learning intervention for subsequent design cycles.

3.6 Data Analysis Methods

The study employed both quantitative and qualitative approaches to data analysis in accordance with the mixed-methods orientation of Design-Based Research (DBR). Quantitative analyses were conducted to determine the extent to which students' conceptual understanding changed under different instructional conditions, whereas qualitative analyses were used to explain why such changes occurred and to identify the aspects of the intervention that facilitated or constrained learning. Consequently, the integration of both forms of analysis was consistent with the fundamental purpose of DBR, which is not only to evaluate the effectiveness of an intervention but also to generate insights for its continuous refinement.

3.6.1 Quantitative Data Analysis

Responses obtained from the conceptual understanding and misconception diagnostic test were first prepared and categorized according to the accuracy of students' answers and the scientific validity of their reasoning. Accordingly, students' responses were classified into three categories: scientific conception, partial understanding, and misconception. Based on these classifications, two composite measures were generated. The first was the conceptual understanding score, which represented the number of items answered correctly with scientifically acceptable reasoning, whereas the second was the misconception index, which reflected confidently held incorrect responses.

Subsequently, descriptive statistics, including means and standard deviations, were computed to summarize students' pre-test and post-test performances. Prior to inferential analyses, the normality of the data was examined using the Shapiro–Wilk test.

To determine the appropriate inferential statistical test, normality of the data was assessed using the Shapiro-Wilk test. Because the primary inferential analysis involves paired comparisons, normality was assessed on the difference scores (Post − Pre) for each category, which is the distribution that the paired-samples t-test assumes to be normally distributed. Table 3.2 presents the Shapiro-Wilk results for the difference scores.

Table 3.2 *Shapiro-Wilk Normality Test Results for Difference Scores (Post − Pre) by Category (N = 50)*

Difference Variable (Post − Pre)	W	p-value	Normal?	Skewness
Diff – Cat 1 Gene Structure, Function & Expression	0.9745	.350	**Yes**	−0.173
Diff – Cat 2 Mendelian Genetics & Probability	0.9664	.164	**Yes**	−0.606
Diff – Cat 3 Meiosis, Gametes & Fertilization	0.9789	.507	**Yes**	−0.155
Diff – Cat 4 Genetic Variation, Mutation & Environment	0.9699	.230	**Yes**	−0.254
Diff – Overall Total	0.9735	.318	**Yes**	−0.264

Note. *W = Shapiro-Wilk statistic. All difference scores were normally distributed (p > .05). Skewness values close to zero indicate symmetrical distributions.*

All five difference score distributions were normally distributed (all $W \geq .966$, all $p > .05$), with low absolute skewness values ranging from −0.606 to −0.155. Although visual inspection of individual pre- and post-test score distributions showed some deviation from normality in certain variables, the normality of difference scores satisfies the key assumption for the paired-samples t-test. Accordingly, parametric statistical analyses were deemed appropriate for all subsequent inferential tests.

Depending on the distribution of the data, within-group changes in conceptual understanding and misconception scores were analyzed using paired-sample t-tests for normally distributed data or Wilcoxon signed-rank tests when the assumption of normality was violated. These analyses enabled the researcher to determine whether significant improvements had occurred following the intervention.

Furthermore, effect sizes were calculated to determine the practical significance of the observed differences. Cohen's d was computed for paired-sample t-tests, whereas eta-squared was calculated for non-parametric analyses. Thus, the magnitude of change was assessed in addition to statistical significance, providing a clearer picture of the educational importance of the intervention.

3.6.2 Qualitative Data Analysis

Qualitative data obtained from classroom observations, interviews, and focus group discussions were analyzed thematically to provide a deeper understanding of students' learning experiences and the implementation of the intervention. Observation notes were first organized and coded using a descriptive coding scheme derived from the inquiry process and the technological components employed during instruction. In particular, the coding focused on how teachers facilitated inquiry phases, how students interacted during learning tasks, the extent to which technology supported investigation and conceptual understanding, and moments in which students demonstrated difficulties, confusion, or conceptual shifts. Consequently, the observation data provided contextual explanations for the quantitative findings and documented the practical realities of implementing the intervention.

Similarly, data obtained from interviews and focus group discussions were documented, transcribed, and analyzed thematically. Emerging themes were identified through repeated reading and coding of participants' responses. Thereafter, themes were compared across instructional groups and between pre- and post-intervention periods to reveal differences in students' understanding of genetics concepts and their experiences with the learning environments. In this way, qualitative findings complemented the quantitative results and provided valuable insights for refining the Technology-Enhanced Guided Inquiry-Based Learning intervention in subsequent design cycles.

3.7 Design of the Technology-Enhanced Guided Inquiry-Based Learning Intervention

The Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) intervention was developed and implemented following the principles of Design-Based Research (DBR). The intervention was carried out over a period of two months and underwent two iterative design cycles. Rather than treating the intervention as a fixed instructional package, evidence gathered during implementation was used to refine and improve subsequent lessons. Consequently, the design was recycled twice, allowing modifications to be made in response to students' learning difficulties and classroom realities.

Lessons were organized around the phases of guided inquiry, namely orientation and questioning, investigation, explanation, and reflection, with technology serving as an integral component of the learning process rather than merely a supplementary resource. Various scaffolding tools, including question prompts, investigation worksheets, data tables, and structured reflection activities, were incorporated to support students' inquiry and conceptual development.

Preparation Phase

Prior to implementation, several preparatory activities were undertaken. These included consultation with stakeholders and obtaining approval from the relevant administrative bodies. Teachers and students were briefed about the purpose and procedures of the study, and schedules were aligned with regular school activities. Consent and assent procedures were completed, while TE-GIBL lesson materials were developed and adapted to fit the Grade 11 genetics curriculum. In addition, simulation videos, animations, and other scaffolding supports were prepared, and formative assessment tools were developed. Small-scale pilot testing was conducted to evaluate the clarity, timing, and usability of the instructional materials. Furthermore, a conceptual understanding test was developed based on a detailed test blueprint aligned with curriculum objectives and documented misconceptions in genetics, and the instrument was subsequently reviewed to establish its validity and reliability.

Baseline Measurement

Before the instructional unit commenced, a single pre-test was administered to establish students' baseline conceptual understanding and identify pre-existing misconceptions regarding genetics concepts.

Micro-Iterative Implementation and Refinement Process

The intervention was implemented over two months through two DBR cycles. Instead of organizing the study into large and isolated cycles, refinement occurred continuously between successive instructional periods. Following each lesson, formative evidence was collected from classroom observations, student artifacts such as worksheets and written explanations, and teacher reflective notes. These sources provided insights into implementation fidelity, classroom discourse, students' engagement, and the effectiveness of scaffolding strategies.

Based on the analysis of these data, instructional modifications were introduced in subsequent lessons. Specifically, inquiry prompts were revised, scaffolding strategies were adjusted, persistent misconceptions were explicitly addressed, pacing and time allocation were modified, simulation navigation guidance was improved, and collaborative discussion norms were strengthened. Through these two cycles of implementation and refinement, the intervention evolved in response to students' needs and classroom constraints.

Intervention Procedures

The main intervention employed in this study was Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL), which aimed to improve Grade 11 students' conceptual understanding of selected genetics concepts and reduce misconceptions. The intervention engaged students in a structured inquiry process consisting of orientation, conceptualization, investigation, explanation, and reflection stages. During instruction, students explored concepts such as DNA–gene–chromosome relationships, meiosis and genetic variation, and Mendelian inheritance through guided inquiry activities that required them to formulate questions, generate hypotheses, analyze evidence, construct explanations, and reflect on their learning. Evidence obtained from classroom observations, students' work, interviews, and conceptual understanding assessments informed the refinement of the intervention throughout the two design cycles.

Technology was embedded throughout each inquiry phase to facilitate the understanding of abstract and difficult-to-visualize genetics concepts. During the orientation and questioning phase, PowerPoint presentations and short instructional videos were used to introduce phenomena, stimulate curiosity, and activate prior knowledge. During the investigation phase, students interacted with simulation videos and animations that illustrated dynamic processes such as meiosis, chromosome movement, allele segregation, genetic variation, and inheritance patterns. These technologies enabled students to observe and investigate biological processes that are otherwise inaccessible through direct observation. During the explanation phase, multimedia presentations and visual representations supported students in interpreting evidence and constructing scientific explanations. Finally, during the reflection phase, structured worksheets and guided discussions were used to encourage students to evaluate their understanding and identify remaining misconceptions.

Therefore, technology functioned not merely as a presentation tool but as an investigative and conceptual support mechanism that enhanced students' engagement and promoted meaningful understanding of genetics concepts. This continuous process of implementation, evaluation, and refinement reflected the core principles of DBR and allowed the intervention to evolve responsively within authentic classroom settings.

The overall process followed a cycle of implementation, evaluation, reflection, and redesign, thereby ensuring that instructional improvements were systematically incorporated into subsequent lessons. Such micro-iterations were consistent with the fundamental principles of Design-Based Research and enabled the intervention to be continuously refined within the realities of everyday classroom practice.

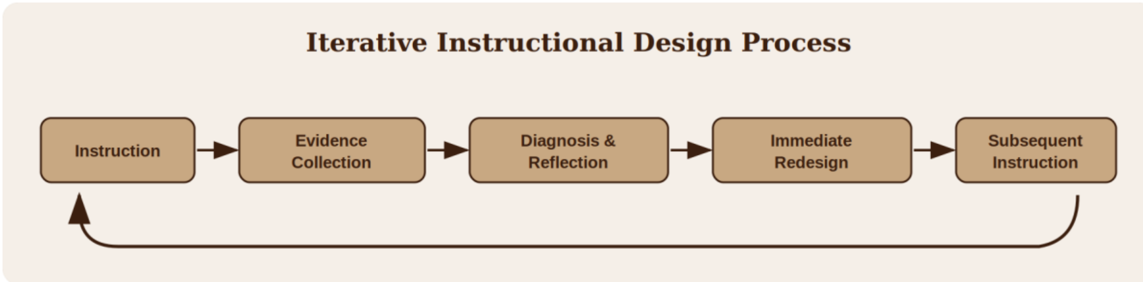

Figure2. Iterative Instructional Design Process

3.8 Ethical Considerations

The study had followed standard ethical practices for school-based research. Approval was obtained from the relevant institutional review board and from the participating schools before any data was collected. Because the work takes place in real classrooms, the ethical approach focuses on transparency, voluntary participation, and minimizing disruption to normal teaching.

Informed consent and assent

Consent was obtained at three levels:

1. **School management:** approval to conduct the study and use school facilities.
2. **Teacher:** consent to participate in the instructional activities, observations, and optional reflections.
3. **Students:** assent from students and consent from parents or guardians when required by the school.

Students were told that participation was voluntary and that choosing not to participate didn’t affect their grades or relationship with the school.

Confidentiality and anonymity

All student and teacher information was kept confidential. Names weren’t appeared in any report, and all data were stored using codes instead of personal identifiers. Only the researcher and authorized supervisors had had access to raw data. Digital files were stored on password-protected devices.

Right to withdraw

Students might withdraw from the study at any time without penalty. They might had skipped any interview question that makes them uncomfortable.

Minimizing disruption

All lessons had followed the school timetable. The intervention had taught by the regular biology teacher so that students had experienced instruction in a familiar environment.

Data use and reporting

Data were used only for research and academic reporting. Findings and results were presented honestly, without exaggeration, and had reflected both strengths and limitations of the intervention in real school settings.

CHAPTER 4

RESULTS

4.1 Introduction

This chapter presents the quantitative and qualitative results of the study investigating the effectiveness of Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) in reducing Grade 11 students' misconceptions and enhancing conceptual understanding about genetics. Results are organized to address each of the three specific objectives:

(1) Identifying students' initial conceptual understanding and misconceptions; (2) determining the effects of TE-GIBL on conceptual understanding; and (3) examining gains in conceptual understanding and reduction in misconceptions following the intervention and draw on four data sources: (1) the two-tier genetics diagnostic test (pre- and post-test); (2) student focus group discussions and semi-structured interviews; (3) semi-structured teacher interviews; and (4) structured classroom observation checklists.

The quantitative analyses were conducted using IBM SPSS Statistics Version 25; with category-level computations conducted using Python. The significance level was set at $\alpha = .05$ for all inferential tests. Qualitative data collected through focus group discussions (FGD) and semi-structured interviews with students were analyzed and are presented alongside statistical findings to provide full information of students' learning experiences and conceptual change.

4.2 Descriptive Statistics

Descriptive statistics were calculated to examine students' genetics achievement scores before and after the TE-GIBL intervention, both at the overall level and across the four genetics concept categories. Table 4.1 presents means, standard deviations, minimum and maximum scores, medians, and maximum possible scores for each variable.

Table 4.1 *Descriptive Statistics of Overall and Category-Level Genetics Scores (N = 50)*

Variable	N	Mean	SD	Min	Max	Median	Max Possible
Overall Score							
Pre-test (GEN_Pre_Total)	50	**16.64**	6.62	8	37	15.0	40
Post-test (GEN_Post_Total)	50	**25.24**	8.54	3	38	27.5	40
By Genetics Category							
Cat 1 – Gene Structure, Function & Expression_ pre	**50**	**4.00**	2.08	0	9	4.0	8
Cat 1 – Gene Structure, Function & Expression_post	**50**	**6.40**	2.13	1	10	7.0	10
Cat 2 – Mendelian Genetics & Probability_pre	**50**	**5.44**	2.73	1	11	5.0	14
Cat 2 – Mendelian Genetics & Probability_post	**50**	**7.82**	3.06	1	12	8.5	12
Cat 3 – Meiosis, Gametes & Fertilization_pre	**50**	**3.42**	2.22	0	10	3.0	8
Cat 3 – Meiosis, Gametes & Fertilization_post	**50**	**6.12**	2.69	1	10	6.0	10
Cat 4 – Genetic Variation, Mutation & Environment_pre	**50**	**3.78**	2.22	0	10	3.0	10
Cat 4 – Genetic Variation, Mutation & Environment_post	**50**	**4.90**	2.11	0	8	6.0	8

Note. *Pre-test max scores: Cat 1 = 8, Cat 2 = 14, Cat 3 = 8, Cat 4 = 10, Overall Total = 40. Post-test max scores: Cat 1 = 10, Cat 2 = 12, Cat 3 = 10, Cat 4 = 8, Overall Total = 40. The pre- and post-tests are parallel forms; item counts per category differ because distinct items measuring the same construct were used.*

At the overall level, the mean score increased substantially from 16.64 (SD = 6.62) at pre-test to 25.24 (SD = 8.54) at post-test, representing a mean gain of 8.6 points on a 40-point scale. The higher post-test standard deviation indicates that students responded differentially to the intervention, with some achieving near-ceiling performance.

At the category level, all four genetics concept areas showed improvement. Category 1 (Gene Structure, Function & Expression) improved from M = 4.00 (50.0% of maximum) to M = 6.40 (64.0% of maximum). Category 2 (Mendelian Genetics & Probability) showed the lowest pre-test performance at M = 5.44 (38.9% of maximum), rising to M = 7.82 (65.2% of maximum) post-intervention. Category 3 (Meiosis, Gametes & Fertilization) improved from M = 3.42 (42.8% of maximum) to M = 6.12 (61.2% of maximum). Category 4 (Genetic Variation, Mutation & Environment) improved from M = 3.78 (37.8% of maximum) to M = 4.90 (61.3% of maximum), recording the smallest absolute mean gain of 1.12 points.

4.3 Students' Initial Conceptual Understanding and Misconceptions

The first specific objective of this study was to identify Grade 11 students' initial conceptual understanding and common misconceptions about selected genetics concepts. This was addressed through pre-test descriptive statistics and frequency analysis of two-tier item scores.

4.3.1 Pre-test Performance

As presented in Table 4.1, students' pre-test mean scores across all categories ranged from 37.8% to 50.0% of the maximum possible scores. The overall pre-test mean of 16.64 out of 40 (41.6%) indicates that students entered the intervention with substantially below-average conceptual understanding of genetics. Category 2 (Mendelian Genetics & Probability) recorded the weakest pre-test performance at 38.9% of the maximum, while Category 1 (Gene Structure) was relatively stronger at 50.0%, suggesting students had more exposure to foundational gene concepts.

4.3.2 Misconception Frequency at Pre-test

The two-tier diagnostic format allowed identification of three performance levels per item: Score 0 both the content question (Tier 1) and the reasoning question (Tier 2) answered incorrectly, indicating a misconception or complete lack of understanding; Score 1 only one tier answered correctly, indicating partial or fragmented understanding; and Score 2 both tiers answered correctly, indicating full conceptual understanding.

Table 4.4 provides the full frequency distribution, but key pre-test findings are highlighted here.

Before the intervention, 45.4% of all student-item responses received a Score of 0, indicating pervasive misconceptions across all categories. Category 2 (Mendelian Genetics) had the highest proportion of Score 0 responses at 51.1%, followed by Category 4 (Genetic Variation) at 46.4%, Category 3 (Meiosis) at 44.5%, and Category 1 (Gene Structure) at 35.0%. Only 22.0% of pre-test responses received a Score of 2, confirming that full conceptual understanding was rare before the intervention.

4.3.3 Qualitative Corroboration: Initial Misconceptions

The conducted focus group discussions before the intervention also revealed students' initial conceptual difficulties. When asked to explain what a gene is and how it differs from a chromosome, students frequently conflated the two concepts:

> *"I thought genes and chromosomes were the same thing like genes are just another name for chromosomes. I was confused about which one is inside the other."* **(FGD, SA)**

"For me, if a trait is dominant it always appears in every generation. I did not know that a dominant allele can be hidden if the person is heterozygous." **(FGD2, SB)**

Similarly, during pre-intervention interviews, students expressed deterministic thinking about probability in genetics:

> *"If the ratio is 3:1, I thought that means from four children, exactly three will have the trait and one will not. I did not understand it is a probability, not a fixed number."* **(I, SC)**

These qualitative accounts go hand with hand with the high Score 0 frequencies observed in the pre-test, particularly in Category 2 (Mendelian Genetics), and confirm that students entered the intervention holding well-established high misconceptions that the TE-GIBL approach needed to address.

4.3.4 Teacher Interview: Observed Pre-intervention Misconceptions

Semi-structured interviews with the biology teacher who implemented the TE-GIBL intervention provided a professional perspective on students' pre-intervention difficulties. The teacher had years of experience teaching biology at the secondary level and had observed genetics instruction across multiple cohorts prior to this study.

> *"Before we started the intervention, I tested what students knew by asking them simple questions in class. Most of them had a fundamental confusion they believed that a dominant gene was a stronger or bigger gene that physically pushed the recessive one away. They could not understand it as a relationship of expression, not physical dominance. This was very common; I would say at least three-quarters of the class held this belief."* **(TI)**

"The probability concept in Mendelian genetics was the hardest for students. They kept insisting that if I cross two heterozygous parents, I will always get exactly one recessive child out of four. I had tried to explain it before using the textbook, but the words alone were not enough to change this deeply held belief." **(TI)**

These teacher observations corroborate both the quantitative pre-test findings and the student qualitative accounts, confirming that misconceptions regarding dominance, Mendelian probability, and meiosis were pervasive, deeply rooted, and recognizable from an experienced educator's perspective across all class groupings not isolated to particular students.

4.3.5 Classroom Observation Findings: Session 1

Structured classroom observations during the first TE-GIBL session further documented the starting point of students' conceptual understanding.

Session 1 observations confirmed low levels of student engagement with inquiry tasks, rare peer scientific discussion, and high surfacing of prior misconceptions during the engage phase of the first unit. Students' confidence in formulating explanations was low, and their engagement with conceptual conflict activities was minimal consistent with students encountering a radically different instructional format from the didactic teaching they were adapted to. The teacher role in Session 1 was predominantly lecture-based, reflecting the transition period at the onset of guided inquiry implementation.

4.4 Objective 2: Effect of TE-GIBL on Students' Conceptual Understanding

The second specific objective was to determine the effects of TE-GIBL on students' conceptual understanding of genetics. This was examined using paired-samples t-tests comparing pre- and post-test scores at both the overall and category levels, supported by effect size analysis.

4.4.1 Paired-Samples t-Test Results

Table 4.3 presents the results of the paired-samples t-tests conducted for the overall total and each of the four genetics categories.

Table 4.3 *Paired-Samples t-Test Results: Pre- vs Post-test Scores by Genetics Category (N = 50)*

Category	Pre-test M (SD)	Post-test M (SD)	Mean Diff.	T	Df	P	Sig.	95% CI
Cat 1 – Gene Structure, Function & Expression	4.00 (2.08)	6.40 (2.13)	**+2.40**	5.456	49	<.001	***	[1.54, 3.26]
Cat 2 – Mendelian Genetics & Probability	5.44 (2.73)	7.82 (3.06)	**+2.38**	4.498	49	<.001	***	[1.34, 3.42]
Cat 3 – Meiosis, Gametes & Fertilization	3.42 (2.22)	6.12 (2.69)	**+2.70**	5.021	49	<.001	***	[1.65, 3.75]
Cat 4 – Genetic Variation, Mutation & Environment	3.78 (2.22)	4.90 (2.11)	**+1.12**	2.832	49	.007	**	[0.34, 1.90]
Overall Total	**16.64 (6.62)**	**25.24 (8.54)**	**+8.60**	**5.763**	49	**<.001**	***	[5.68, 11.52]

Note. *M = Mean; SD = Standard Deviation in parentheses; Diff. = Mean difference (Post − Pre); CI = 95% Confidence Interval for the mean difference; df = 49 for all tests. ** p < .01. *** p < .001 (two-tailed).*

The paired-samples t-test revealed statistically significant improvement from pre- to post-test for all four categories and the overall total score. The overall genetics score increased from M = 16.64 (SD = 6.62) to M = 25.24 (SD = 8.54), a mean difference of 8.6 points, t(49) = 10.935, $p < .001$, 95% CI [5.68, 11.52].

At the category level, Categories 1, 2, and 3 all achieved $p < .001$. Category 1 (Gene Structure, Function & Expression) showed a mean increase of 2.40 points, t(49) = 5.456, $p < .001$, 95% CI [1.54, 3.26]. Category 2 (Mendelian Genetics & Probability) improved by a mean of 2.38 points, t(49) = 4.498, $p < .001$, 95% CI [1.34, 3.42]. Category 3 (Meiosis, Gametes & Fertilization) recorded the largest mean gain among the four categories at 2.70 points, t(49) = 5.021, $p < .001$, 95% CI [1.65, 3.75]. Category 4 (Genetic Variation, Mutation & Environment) also showed a significant improvement of 1.12 points, t(49) = 2.832, p = .007, 95% CI [0.34, 1.90], though this was the smallest and least practically significant gain among the four categories.

All 95% confidence intervals excluded zero, confirming that the observed improvements are unlikely to be due to chance. The finding that all four conceptually distinct genetics domains improved significantly provides strong evidence that TE-GIBL produced broad-based learning gains rather than improvements confined to specific content areas.

4.4.2 Effect Size Analysis

To assess the practical significance of the observed improvements, Cohen's d and Hedges' g were computed for each category and the overall total. Table 4.3 presents the effect size results.

Table 4.3 *Effect Size Analysis: Cohen's d and Hedges' g for Pre- to Post-test Gains by Category (N = 50)*

Category	Pre M	Post M	Mean Diff.	SD Diff.	Cohen's d	Hedges' g	Magnitude
Cat 1 – Gene Structure, Function & Expression	4.00	6.40	**+2.40**	3.11	**0.772**	0.760	**Medium**
Cat 2 – Mendelian Genetics & Probability	5.44	7.82	**+2.38**	3.74	**0.636**	0.626	**Medium**

Category	Pre M	Post M	Mean Diff.	SD Diff.	Cohen's d	Hedges' g	Magnitude
Cat 3 – Meiosis, Gametes & Fertilization	3.42	6.12	**+2.70**	3.80	**0.710**	0.699	**Medium**
Cat 4 – Genetic Variation, Mutation & Environment	3.78	4.90	**+1.12**	2.80	**0.400**	0.394	**Small**
Overall Total	**16.64**	**25.24**	**+8.60**	10.55	**0.815**	0.802	**Large**

Note. *Cohen's d = Mean difference / SD of difference scores (paired-measures formula). Hedges' g = d × J, correction factor J = 0.985 (n = 50). Benchmarks (Cohen, 1988): negligible < 0.20; small = 0.20–0.49; medium = 0.50–0.79; large ≥ 0.80. Mean Diff. = Post-test mean minus Pre-test mean.*

The overall effect size was large (d = 0.815, g = 0.802), indicating that the TE-GIBL intervention had substantial practical significance. Categories 1, 2, and 3 yielded medium effect sizes (d = 0.772, 0.636, and 0.710 respectively), all exceeding the medium threshold of d = 0.50. Category 4 yielded a small effect size (d = 0.400), indicating a more limited practical impact in this domain despite statistical significance. The near-identity of Cohen's d and Hedges' g values (correction factor J = 0.985) confirms effect size estimates are not inflated by the sample size of 50.

4.4.3 Qualitative Corroboration: Perceived Learning Gains

Students' response in post-intervention focus group discussions supported the quantitative evidence of improvement. When asked about their experience of learning genetics through TE-GIBL, several recurring themes emerged:

Theme 1: Increased clarity of abstract concepts.

"Before, when the teacher talked about meiosis, I could not picture it in my mind. But with the simulations and interactive diagrams, I could actually see how chromosomes separate and how gametes are formed. It became very clear." **(FGD, SD)**

"The technology helped me understand Punnett squares much better. I could do many crosses by myself and see the outcomes immediately. In the normal class I only copied from the board without really understanding." **(FGD, SE)**

Theme 2: Transformation of misconceptions.

"I used to think that if your parents both have a dominant trait; you will always have it too. After the activities I realized that was wrong there is a chance of getting the recessive trait if both parents carry it hidden." **(FGD, SF)**

"Now I understand that genes are sections on chromosomes they are not the same thing. I had this wrong for a long time." **(FGD, SG)**

Theme 3: Active engagement and motivation.

"I enjoyed this learning. Usually biology is memorizing, but this time I was doing things, not just listening. I felt like a scientist investigating." **(I, SH)**

4.4.4 Teacher Interview: Observed Effects of TE-GIBL on Student Understanding

The teacher's interview provided a professional observational perspective on the changes in student understanding during and after the intervention:

"The change I noticed most clearly was in Mendelian genetics. In my previous teaching, students could repeat the 3:1 ratio correctly in an exam but could not explain why. After the activities, I saw students spontaneously explaining to each other why the ratio is not always exactly 3:1 in a real family they were using the language of probability correctly and with confidence. That was a breakthrough I had not seen before." **(TI)**

"I noticed that even students who were usually quiet in class became more vocal during the group inquiry activities. They were arguing scientifically not agreeing with each other just to finish the task, but actually challenging each other's reasoning. This kind of discussion is very rare in a conventional genetics lesson." **(TI)**

The teacher accounts corroborate the quantitative improvements and align closely with the student-reported themes of increased clarity, misconception transformation, and active engagement. Importantly, the teacher's perspective adds a comparative dimension contrasting the observed outcomes with those of previous cohorts taught through conventional instruction strengthening the inference that the observed improvements are attributable to the TE-GIBL intervention rather than to general student ability or maturation.

4.4.5 Classroom Observation Findings:

Classroom observations documented a progressive developmental trajectory across the next sessions. The next sessions showed moderate engagement and emerging quality of student explanations, with peer discussion occurring occasionally rather than rarely. A notable turning point was observed between sessions where student engagement shifted from moderate to high, collaborative group work improved from fair to good, and the frequency of evidence of conceptual change shifted from moderate to clearly evident. By the last sessions students were fully engaged with conceptual conflict activities, the teacher had transitioned fully to a facilitation role, and collaboration quality was rated excellent.

4.5 Pre-Post Gains in Conceptual Understanding and Misconception Reduction

The third specific objective was to compare conceptual understanding gains and examine the reduction of misconceptions before and after the TE-GIBL intervention.

Table 4.4 *Frequency of Two-Tier Item Scores (0, 1, 2) by Genetics Category — Pre- and Post-test (N = 50)*

Category	Items Pre/Post	Total Resp. Pre/Post	Pre Score 0 n (%)	Pre Score 1 n (%)	Pre Score 2 n (%)	Post Score 0 n (%)	Post Score 1 n (%)	Post Score 2 n (%)
Cat 1 – Gene Structure, Function & Expression	4/5	200/250	70 (35.0%)	73 (36.5%)	57 (28.5%)	61 (24.4%)	58 (23.2%)	131 (52.4%)
Cat 2 – Mendelian Genetics & Probability	7/6	350/300	179 (51.1%)	98 (28.0%)	73 (20.9%)	63 (21.0%)	83 (27.7%)	154 (51.3%)
Cat 3 – Meiosis, Gametes & Fertilization	4/5	200/250	89 (44.5%)	64 (32.0%)	47 (23.5%)	60 (24.0%)	74 (29.6%)	116 (46.4%)
Cat 4 – Genetic Variation,	5/4	250/200	116 (46.4%)	91 (36.4%)	43 (17.2%)	48 (24.0%)	59 (29.5%)	93 (46.5%)

Category	Items Pre/Post	Total Resp. Pre/Post	Pre Score 0 n (%)	Pre Score 1 n (%)	Pre Score 2 n (%)	Post Score 0 n (%)	Post Score 1 n (%)	Post Score 2 n (%)
Mutation & Environment								
Overall Total	20/20	1000/1000	**454 (45.4%)**	**326 (32.6%)**	**220 (22.0%)**	**232 (23.2%)**	**274 (27.4%)**	**494 (49.4%)**

Note. *Score 0 = both Tier 1 (content) and Tier 2 (reason) incorrect — indicates a misconception or absence of understanding. Score 1 = only one tier correct — indicates partial/fragmented understanding. Score 2 = both tiers correct — indicates full conceptual understanding. Items Pre/Post = number of items per category in pre-test / post-test. Total Resp. = N × items. Counts represent student×item responses.*

4.5.1 Overall Misconception Reduction

At the overall level, Score 0 responses decreased from 454 (45.4%) to 232 (23.2%) — a reduction of 22.2 percentage points, nearly halving the rate of misconceptions. Simultaneously, Score 2 responses (full understanding) more than doubled from 220 (22.0%) to 494 (49.4%). Score 1 responses (partial understanding) declined modestly from 326 (32.6%) to 274 (27.4%), indicating that students who previously held fragmented understanding largely advanced to full understanding rather than remaining in a partial state.

4.5.2 Category-Level Misconception Analysis

Category 1 (Gene Structure, Function & Expression): Score 0 responses decreased from 70 (35.0%) to 61 (24.4%), a reduction of 10.6 percentage points. Score 2 responses increased from 57 (28.5%) to 131 (52.4%), nearly doubling. The relatively low pre-test misconception rate in this category reflects students' prior familiarity with basic gene concepts.

Category 2 (Mendelian Genetics & Probability): This category showed the most powerful transformation. Score 0 responses decreased from 179 (51.1%) to 63 (21.0%), a reduction of 30.1 percentage points the largest misconception reduction of all categories. Score 2 responses grew from 73 (20.9%) to 154 (51.3%). The pre-test majority of Score 0 responses in this category confirms that Mendelian genetics was the most misconception-laden domain and simultaneously the area where TE-GIBL intervention had its greatest impact.

Category 3 (Meiosis, Gametes & Fertilization): Score 0 responses decreased from 89 (44.5%) to 60 (24.0%), a reduction of 20.5 percentage points. Score 2 responses increased from 47 (23.5%) to 116 (46.4%). The t-test for this category yielded the largest mean gain (Δ = 2.70) among the four categories, and the frequency data confirm a substantial shift from misconception toward full understanding.

Category 4 (Genetic Variation, Mutation & Environment): Score 0 responses decreased from 116 (46.4%) to 48 (24.0%), a reduction of 22.4 percentage points. Score 2 responses increased from 43 (17.2%) to 93 (46.5%). Notably, despite this category having the smallest effect size (d = 0.400) based on total score, the misconception frequency reduction was substantial, suggesting that TE-GIBL was effective at addressing misconceptions in this area even if mean score gains were modest.

4.5.3 Qualitative Corroboration: Misconception Reduction

Students' response in post-intervention interviews specifically addressed their awareness of having held and overcome misconceptions during the TE-GIBL activities:

> *"At the beginning I believed that mutations are always bad — they cause cancer or diseases. But I learned through our research activity that mutations can be neutral or even beneficial. I was completely wrong before."* **(I, SI)**

> *"I thought meiosis and mitosis were the same process, just with different names. The simulation showed me clearly how meiosis produces four different cells and why that matters for reproduction. Now I can explain the difference without any confusion."* **(FGD, SJ)**

> *"The 3D model of DNA replication was the moment I understood it. I had read it many times in the textbook but it did not make sense. Seeing it move and being able to control the speed changed everything."* **(I, S L)**

4.5.4 Teacher Interview: Observed Misconception Reduction

The teacher's accounts specifically addressed the process and evidence of misconception reduction observed during and after the intervention:

"The most satisfying moment in the entire intervention was during the Mendelian genetics unit. I had given students a prediction activity before the simulation video they predicted the outcomes of many crosses and almost all predicted exact numbers like 'three out of four.' Then they ran the simulation video and saw that in reality the outcomes varied. I watched their faces change as the data contradicted their predictions. That moment of confusion turning into understanding that is what I had been trying to achieve for years with chalk and talk, and I had never seen it happen so clearly before." **(T I)**

4.5.5 Classroom Observation: Evidence of Conceptual Change in the last Sessions

Classroom observations during the final two sessions documented observable behavioral evidence of conceptual change a critical form of triangulation that complements both the test score data and the retrospective interview accounts. During the first of the last session, the observer recorded multiple instances of students spontaneously correcting each other's statements using scientifically accurate reasoning: for example, a student in one group was observed stating that 'meiosis produces copies,' and was immediately challenged by a peer who referenced the simulation to explain that meiosis produces cells with half the chromosomes and different genetic combinations. This type of peer correction using evidence-based reasoning was not observed in Session 1, indicating a qualitative shift in the discourse norms of the classroom from authority-based acceptance of teacher statements to evidence-based peer argumentation.

By the last session, the observation checklist recorded excellent collaboration quality, very active engagement with conceptual conflict activities, and high student confidence in reasoning explanations than the first session.

CHAPTER FIVE

DISCUSSION

5.1 Introduction

This chapter discusses the findings of the study in relation to the three specific research objectives, the existing body of literature, and the theoretical framework supporting the investigation. The central concern of this study was to examine the effectiveness of Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) as an instructional approach for improving Grade 11 students' conceptual understanding of genetics and reducing their misconceptions about four genetics concept categories:

(1) Gene Structure, Function & Expression;

(2) Mendelian Genetics & Probability;

(3) Meiosis, Gametes & Fertilization; and

(4) Genetic Variation, Mutation & Environment.

The discussion begins by locating the genetics content areas in the context of documented learning difficulties and misconceptions. It then examines the three specific objectives are subsequently addressed as distinct discussion subsections, each integrating qualitative accounts and quantitative findings alignments with literature, and notable contradictions and it was drawn on all four data sources the two-tier genetics diagnostic test, student focus group discussions and interviews, teacher semi-structured interviews, and classroom observation checklists to construct a multi-layered interpretation of the findings. Where appropriate, the discussion features both alignments with and contradictions to existing literature, and identifies implications for the design-based research cycle and future iterations of the TE-GIBL intervention.

5.2 The Challenge of Teaching and Learning Genetics: Why Misconceptions Persist

Before directly diving to interpretation and discussion of the results it is necessary to understand why genetics presents particular conceptual challenges for secondary school learners and why misconceptions in this domain are so persistent and resistant to traditional instruction.

Genetics involves an array of abstract concepts that span multiple levels of biological organization simultaneously, from DNA molecules and genes, to chromosomes, to traits, to populations. Students must mentally integrate these invisible molecular, cellular, and organismal processes. Tsui, C. Y., y Treagust, (2005) identified this multi-level abstraction as a central reason why genetics remains among the most difficult topics in secondary biology, with students frequently failing to coordinate understanding across levels. Students often confuse genes with chromosomes, treating them as the same rather than understanding the hierarchical relationship in which genes are segments of chromosomes (Bahar et al., 2010; Stavy, 2010). Similarly, students tend to think of dominant alleles as physically overwhelming recessive alleles rather than understanding that dominance is a functional, not a physical, relationship (Lewis & Wood-robinson, 2010).

The probabilistic nature of Mendelian genetics presents an additional cognitive barrier. Students are adapted to deterministic causal reasoning like A x B, and find it conceptually difficult to accept that identical crosses can produce different outcomes due to the random nature of gamete formation and fertilization (Kampourakis & Zogza, 2008). This leads to the well-documented deterministic misconception in which students interpret Mendelian ratios (e.g., 3:1) as exact predictions rather than probabilistic tendencies across large numbers of offspring.

Meiosis and fertilization are similarly challenging. Students frequently conflate meiosis with mitosis, believing both processes produce genetically identical cells (Dikmenli, 2010). The concept that meiosis halves the chromosome number and that fertilization restores it requires students to track chromosomal content across multiple sequential events a demand on working memory and sequential reasoning that exceeds the capacity of many learners when relying solely on verbal or textual instruction (Stewart, 1982).

Genetic variation and mutation are the most abstract of the four categories. Students commonly hold the misconception that all mutations are harmful and disease-causing, influenced by popular media representations of mutation (Kampourakis & Zogza, 2008). The concept that mutations are the ultimate source of genetic variation, that selection acts on this variation, and that environmental factors interact with genotype to produce phenotype requires integration of multiple concepts that students rarely encounter in coherent, structured ways in traditional instruction.

These accumulated conceptual challenges like multi-level reasoning, abstraction, probabilistic reasoning and thinking and integration of distant concepts explain why the pre-test findings in this study showed that 45.4% of all student-item responses received Score 0 (both content and reasoning incorrect), with the highest misconception rate in Mendelian Genetics (51.1%) and the lowest in Gene Structure (35.0%). The pre-test data confirm that this sample of Grade 11 students entered the intervention with exactly the types of misconceptions documented in the international genetics education literature, situating the present study within a well-established empirical context.

5.3 Students' Initial Conceptual Understanding and Common Misconceptions

The first objective was to identify Grade 11 students' initial conceptual understanding and common misconceptions about selected genetics concepts before the TE-GIBL intervention.

The findings of pre-test documented in Chapter 4 are highly reliable with the international genetics education literature. The overall pre-test mean of 41.6% of the maximum score indicates weak conceptual understanding, consistent with findings by Smith & Knight, (2012) reported that secondary students typically score below 50% on conceptual genetics assessments prior to targeted instruction. The 45.4% rate of Score 0 responses (both content and reasoning incorrect) in this study aligns with Chattopadhyay, (2005) finding that over 40% of secondary students in developing country contexts held fundamental genetics misconceptions, and with Bahar et al., (2010) documentation of widespread misconceptions in Turkish secondary students across precisely the concept areas examined here.

The specific pattern of misconceptions identified qualitatively the confusion between genes and chromosomes, misinterpretation of dominant–recessive relationships and the inability to reason probabilistically about Mendelian ratios mirrors findings from multiple international studies (Garvin-doxas & Klymkowsky, 2008; Lewis & Wood-robinson, 2010; Stavy, 2010). The fact that students in this Ethiopian Grade 11 sample hold the same misconceptions documented in studies from different countries like Turkey, the United Kingdom, the United States, and India suggests that these are not culturally specific errors rather reflect basic cognitive challenges in reasoning about genetics at the molecular and probabilistic levels.

The high pre-test misconception rate in Category 2 (Mendelian Genetics, 51.1% Score 0) is significant and consistent with Tsui, C. Y., y Treagust, (2005) identification of Mendelian genetics as the single most misconception-laden domain in secondary biology worldwide. The lowest pre-test misconception rate was in Category 1 (Gene Structure, 35.0%), probably reflecting the greater emphasis placed on the basics of gene and DNA structure in the country's secondary biology curricula relative to probability and inheritance patterns of genetics.

The teacher interview data add a dimension not available in published student-only studies: confirmation from an experienced biology educator that these specific misconceptions are stable across cohorts and resistant to conventional re-teaching. The teacher's observation that students could pass traditional examinations by memorizing correct answers while still holding the underlying misconception is consistent with Driver et al, (1994) documentation that misconceptions routinely coexist with correct test responses in traditional assessment formats precisely why the two-tier diagnostic test format was essential in this study.

A notable inconsistency exists between the pre-test findings and the expectation that prior curriculum exposure would substantially reduce misconceptions. Ethiopian Grade 11 students have already completed basic genetics instruction in previous grades, yet the data from pre-test show that the prior exposure provided little towards the persistent misconceptions. This contradicts a common assumption in curriculum design that revisiting content in later grades automatically builds on prior understanding and is instead consistent with Driver et al, (1994) much documentation that misconceptions resist correction through traditional re-teaching approaches and persisting even after formal instruction precisely because they are not directly addressed as misconceptions. Students in this study held confident but incorrect beliefs, not merely gaps in knowledge a qualitatively different problem that requires qualitatively different instructional solutions.

A further contradiction concerns the relatively stronger pre-test performance in Category 1 (Gene Structure) compared to Category 4 (Genetic Variation). Intuitively, one might expect gene structure to be more abstract and therefore more prone to misconceptions than genetic variation. The reversal observed here may reflect the greater emphasis on DNA and gene structure in textbook-based instruction at the expense of variation and mutation, leaving students relatively more informed about gene structure but no less prone to the specific misconceptions (such as conflation of genes and chromosomes) that the two-tier test was designed to detect.

5.4 Effects of TE-GIBL on Students' Conceptual Understanding

The second objective of the study was to determine the effects of TE-GIBL intervention on students' conceptual understanding of genetics. The findings presented in Chapter 4 provide strong statistical and practical evidence that TE-GIBL significantly improved conceptual understanding across all four genetics categories.

The statistically significant improvements across all four categories ($p < .001$ for Categories 1–3; $p = .007$ for Category 4) with a large overall effect size ($d = 0.815$) hold an evidence of TE-GIBL's effectiveness. The finding is consistent with a body of research supporting inquiry-based instruction in secondary biology. Minner et al., (2010) meta-analysis of 138 studies found that inquiry-based science instruction consistently and significantly outperformed traditional didactic approaches, with effect sizes typically in the medium range ($d = 0.30–0.60$). The large overall effect size obtained in the present study ($d = 0.815$) exceeds this typical range, suggesting that the addition of technology enhancement to guided inquiry produced an increased effect beyond what guided inquiry alone might achieve.

This amplification also go hand in hand with Smetana & Bell, (2014) meta-analysis of computer simulations in science education, which found that simulation-enhanced instruction produced larger effect sizes than non-simulation instruction, particularly for conceptual understanding outcomes involving abstract processes. The TE-GIBL intervention combined both the process advantages of guided inquiry (structured investigation, collaborative reasoning, and formative feedback) and the representational advantages of technology (dynamic visualization) a combination that theoretical frameworks predict should be particularly effective for abstract, process-based content such as genetics (Jonassen, 2000).

The differential effect sizes across categories (medium for Categories 1–3, small for Category 4) warrant close examination. Categories 1–3 involve processes that are well-suited to dynamic visualization: DNA replication (Category 1), Punnett square crosses and probability (Category 2), and chromosome movement during meiosis (Category 3) can all be represented as observable, controllable processes in technological environments. Category 4 (Genetic Variation, Mutation & Environment) involves concepts at the population level, how genetic variation accumulates, how mutations propagate through populations, how environment modifies gene expression, which are inherently more abstract and less amenable to direct visualization than molecular or cellular processes. This content-technology match hypothesis, the idea that technology-enhanced instruction is most effective when the technology directly addresses the representational challenge inherent in the content offers a theoretically grounded explanation for the observed differential effectiveness. These improvements were corroborated by student interview accounts of increased clarity and active engagement, teacher accounts of qualitatively superior learning outcomes compared to previous cohorts, and classroom observation data documenting progressive improvement in inquiry engagement and collaboration quality across sessions.

The large overall effect size aligns with findings from comparable technology-enhanced biology interventions in African secondary school contexts. Kibuka-sebitosi & Kibuka-sebitosi, (2010) reported significant improvements in South African students' genetics understanding following simulation-based instruction and Odom & Barrow, (1995) documented substantial gains in US students' meiosis understanding using dynamic visualization tools compared to traditional instruction. The present study extends this evidence to the Ethiopian context, where access to technology-enhanced biology instruction has historically been limited, suggesting that the benefits of TE-GIBL are generalizable across resource contexts when the tools and activities are appropriately designed.

Qualitative accounts from students reinforce the quantitative evidence. The theme of increased conceptual clarity particularly for visual and process-based concepts like meiosis and Punnett crosses aligns with cognitive load theory's prediction that external representations (visualizations) that offload processing demands from working memory enable deeper conceptual processing (Sweller, 1988). Students consistently reported that the transition from passive textbook reading to active technology-based investigation produced a qualitatively different learning experience:

> *"In the normal class I only copied from the board without really understanding. Here I was doing while understanding it myself."* **(FGD, S E)**

This account directly represents the distinction between surface-level procedural learning (copying procedures) and deep conceptual learning (understanding why procedures work).

The teacher's comparative observation that outcomes in this cohort exceeded those of previous cohorts taught through conventional instruction provides qualitative external validity for the quantitative effect size:

> *"The change I noticed most clearly was in Mendelian genetics. In my previous teaching, students could repeat the 3:1 ratio correctly in an exam but could not explain why. After the simulation activities, I saw students spontaneously explaining the probabilistic meaning of the ratio. That was a breakthrough I had not seen before."* **(T I)**

This account captures the distinction between surface procedural learning (recalling ratios) and deep conceptual understanding (explaining why ratios are probabilistic) precisely the distinction that the two-tier test was designed to measure and that the post-test Score 2 increase (from 22.0% to 49.4%) quantifies.

The findings also show some contradiction with literatures. Kirschner et al., (2010) in their paper, argued that minimally guided discovery learning is less effective than explicit instruction for novice learners, primarily because it imposes excessive cognitive load and fails to provide the instructional support that novices require. At face value, this argument might be taken to contradict the present study's positive findings for inquiry-based instruction.

However, this tension is more apparent than real. The TE-GIBL intervention was not minimally guided discovery learning it was guided inquiry with explicit scaffolding, structured questions, formative feedback, and teacher facilitation. This distinction is critical. Hmelo-silver et al., (2007) directly responded to Kirschner et al., (2010) Kirs by demonstrating that well-scaffolded problem-based and inquiry-based learning is substantively different from minimally guided discovery, and that the cognitive load concerns identified by Kirschner et al., (2010) are addressed precisely by the scaffolding and guidance structures that TE-GIBL employs. The present findings align with Hmelo-silver et al.,'s position: guided inquiry, properly scaffolded and supported by technology, produces superior conceptual outcomes compared to traditional instruction.

Another tension, however, exists regarding Category 4 (Genetic Variation, Mutation & Environment). Despite statistical significance ($p = .007$), the small effect size ($d = 0.400$) indicates that the TE-GIBL intervention was substantially less effective for this category than for the others. This finding partially contradicts the general claim that TE-GIBL is uniformly effective for genetics instruction and suggests that the current design is not optimally suited to all genetics content. The available technological tools used in the intervention were better suited to molecular and Mendelian genetics than to population-level genetic variation, gene-environment interaction, and the stochastic nature of mutation. This is a specific and actionable contradiction that the Design-Based Research framework treats not as a failure but as a design insight requiring iterative refinement in the next cycle.

5.5 Effects of TE-GIBL on Addressing Genetics Misconceptions

The third specific objective was to determine the effect of TE-GIBL on addressing Grade 11 students' misconceptions in genetics. This objective was addressed primarily through the two-tier score frequency analysis and qualitative data from focus group discussions and interviews.

5.5.1 Evidence of Misconception Reduction

The data from frequency analysis provides the most convincing evidence. The near-halving of Score 0 responses from 45.4% to 23.2% represents a fundamental shift in students' conceptual understanding, not merely improved test performance. This distinction is essential: a student can increase their test score by moving from Score 0 to Score 1 (learning the correct content answer without understanding the reasoning), without having resolved the underlying misconception. The TE-GIBL intervention produced a shift from Score 0 directly to Score 2 full, well-reasoned understanding across all four categories. This pattern indicates that the intervention addressed the deep structure of misconceptions (the faulty reasoning underlying incorrect answers) rather than merely replacing wrong factual answers with correct ones.

Category 2 (Mendelian Genetics & Probability) with a 30.1 percentage-point reduction in Score 0 responses the largest of all categories, this finding represents a direct counter to the well-documented resistance of Mendelian genetics misconceptions to traditional instruction. Tsui, C. Y., y Treagust, (2005) specifically highlighted the Mendelian genetics domain as one where conceptual change is most difficult to achieve, noting that traditional didactic instruction rarely produces lasting conceptual change in this area. The present study's evidence that TE-GIBL substantially reduced Mendelian misconceptions is therefore both practically significant and theoretically important; suggesting that the combination of interactive Punnett square simulations videos, guided probability inquiry, and explicit conceptual conflict activities can succeed where traditional instruction repeatedly fails.

5.5.2 Qualitative Evidence of Conceptual Change

The qualitative data provide original first-person accounts of the process of conceptual change, not merely its outcomes. Students explicitly had spoken the movement from misconception to understanding, demonstrating the metacognitive awareness that characterizes meaningful learning:

> *"The hardest thing for me was understanding that a probability of 25% does not mean from four children, one will definitely have the trait. I kept getting this wrong. The simulation video where I had watched repeatedly helped me see that probability works over many trials, not just four."* **(FGD, S K)**

This account is particularly instructive. The student identifies the specific nature of the prior misconception (deterministic interpretation of probability), the instructional experience that created cognitive conflict (running many simulated crosses and observing variation in outcomes), and the resulting conceptual transformation (understanding probability as a tendency over many trials). This is a textbook instance of Gertzog, (1982) conceptual change model in action: the existing conception proved inadequate when confronted with evidence (the simulation showed variable outcomes, not the predicted 1-in-4 pattern), and the new conception (probabilistic tendency) became intelligible and plausible through direct experience with the data.

> *"At the beginning I believed that mutations are always bad; they cause cancer or diseases. But I learned that mutations can be neutral or even beneficial. I was completely wrong before."* **(I, S I)**

This account from Category 4 (Genetic Variation and Mutation) is significant precisely because it demonstrates misconception reduction in the category where the quantitative effect size was smallest. While the overall score gains for this category were modest (d = 0.400), individual students clearly achieved conceptual change regarding specific misconceptions (the harmful-mutation belief). This suggests dissociation between overall score gains and misconception reduction in Category 4: the TE-GIBL activities may have been effective at addressing the most prominent misconceptions in this category while less effective at building the broader conceptual scaffolding needed for higher scores.

Future design iterations should prioritize building the population-level genetic reasoning framework, not only correcting specific misconceptions.

The teacher interview data also provide a uniquely valuable account of misconception reduction from the educator's perspective, documenting the classroom processes that the test data cannot capture:

> *"For the mutation misconception, I was particularly impressed. Students came in believing all mutations were harmful this is partly from television and partly from how the textbook presents it. The research activity where students investigated examples of neutral and beneficial mutations in populations completely changed this view for most students. By the end of the session I heard students arguing that sickle cell trait can actually be protective against malaria they had not only corrected their misconception but were applying the new understanding to real-world examples."* **(T I)**

This account illustrates Gertzog, (1982) fruitfulness criterion for conceptual change: students did not merely replace one belief with another but began applying the new conception to generate novel explanations of real-world phenomena (sickle cell protection against malaria). This level of application spontaneous transfer to real-world contexts goes substantially beyond what the post-test score data capture and suggests that the conceptual change achieved in Category 4 may be deeper and more generative than the small effect size (d = 0.400) implies.

The observation checklist findings for the last two sessions provide further evidence of this qualitative shift in understanding. The observer noted multiple instances of students spontaneously correcting each other's misconceptions using simulation-derived evidence for example, a student stating 'meiosis produces copies' was immediately challenged by a peer referencing the cell division animation. This form of peer-based conceptual correction, emergent rather than teacher-directed, represents the highest level of conceptual consolidation observable in a classroom setting.

The overall pattern of misconception reduction across all four categories is strongly consistent with Gertzog, (1982) conditions for conceptual change:

(A) The learner must be dissatisfied with the existing conception; (B) The new conception must be intelligible; (C) It must appear plausible; and (D) It must be fruitful suggesting new ways of understanding phenomena. The TE-GIBL design deliberately operationalized all four conditions. Dissatisfaction was induced through conceptual conflict activities that made students' incorrect predictions visible and testable. Intelligibility was supported through dynamic visualizations that made abstract processes observable and controllable. Plausibility was established through collaborative inquiry and peer discussion, where students constructed and tested explanations together. Fruitfulness was demonstrated when newly understood concepts enabled students to solve novel genetics problems that their prior misconceptions had prevented them from approaching.

The qualitative accounts support the plausibility and fruitfulness conditions. Multiple students described a moment of insight a point at which a previously opaque concept suddenly became clear and opened up new understanding:

> *"When we see the genetics simulation video to breed virtual organisms across many generations, I could see patterns emerging. It was not just memorizing Mendel's laws. I was discovering them myself."* **(FGD, S M)**

The phrase 'discovering them myself' captures the essence of conceptual change through guided inquiry: understanding is constructed by the learner through active investigation, not transferred from teacher to student through exposition. This is consistent with constructivist learning theory (Piaget, 1970; Vygotsky, 1978) and distinguishes meaningful learning from rote memorization.

The classroom observation data document this process across sessions: Session 1 showed 'None observed' for evidence of conceptual change, the next sessions showed 'Minimal' to 'Moderate,' and the last two sessions showed 'Evident.' This progressive trajectory is consistent with the theoretical prediction that conceptual change is a gradual process requiring sustained engagement with counterevidence and new explanatory frameworks.

Despite the overall positive pattern of misconception reduction, the persistence of a substantial proportion of Score 0 responses even at post-test (23.2% overall) needs discussion. A single well-designed intervention cycle cannot be expected to eradicate all misconceptions and in a Design-Based Research framework, this is expected and informative rather than problematic.

The teacher acknowledged this limitation directly:

> *"Some students changed completely you could see it in how they spoke about genetics after the intervention. But a few students, even at the end, still showed signs of the old thinking. I think some misconceptions need more time and more encounters with contradictory evidence before they are fully resolved. One cycle of TE-GIBL is a strong beginning, but not a complete solution."* **(T I)**

This teacher observation is precisely consistent with the Design-Based Research perspective: the first cycle of an intervention identifies what works and what requires refinement, rather than claiming perfection. The residual 23.2% Score 0 rate is not a failure of the intervention but a specific, empirically grounded design target for the next iteration particularly for the most resistant misconceptions in Categories 2 and 4, where culturally reinforced beliefs and cognitively complex probabilistic reasoning create the greatest barriers to change.

The persistence of Score 0 responses is, however, somewhat in tension with theoretical models suggesting that well-designed conceptual conflict interventions produce large-scale misconception resolution (Treagust & Duit, 2008). One possible explanation is that the single-cycle intervention duration was insufficient for the complete restructuring of deeply held misconceptions, particularly for higher-order concepts in Category 4. This is consistent with (Disessa, 2002) knowledge-in-pieces framework, which argues that conceptual change is a slow, iterative process of reorganizing many small knowledge fragments rather than a sudden replacement of one conception with another. A multi-cycle TE-GIBL intervention spanning a full academic year might produce more complete misconception resolution than the single-cycle approach examined here.

5.6 Implications for Design-Based Research

Viewed through the lens of Design-Based Research (Anderson & Shattuck, 2014; Wang & Hannafin, 2005), the findings of this study provide formative evidence for the refinement of the TE-GIBL design in subsequent cycles beyond summative evidence of effectiveness. The key design insights emerging from this study are:

- The core design principles of TE-GIBL (guided inquiry structure, technology-enhanced visualization, collaborative group work, and explicit conceptual conflict activities) produced consistently positive outcomes across three of the four genetics categories and should be preserved in future iterations.
- Category 4 (Genetic Variation, Mutation & Environment) requires targeted redesign. Future iterations should incorporate population genetics simulation tools, gene-environment interaction models, and explicitly structured activities addressing the harmful-mutation misconception and the relationship between mutation, variation, and natural selection.
- The residual 23.2% Score 0 rate at post-test suggests a need for extended intervention duration to achieve more complete misconception resolution, particularly for the most deeply entrenched misconceptions identified in the qualitative data.
- The strong convergence between quantitative and qualitative findings validates the mixed-methods approach and confirms that the two-tier diagnostic test is an appropriate and sensitive instrument for measuring both conceptual understanding gains and misconception reduction in genetic

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

6.1 Conclusion

This study examined the effectiveness of Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) in improving Grade 11 students' conceptual understanding of genetics and reducing misconceptions. Pre-test results revealed widespread misconceptions across major genetics concepts, indicating that students' prior knowledge was largely superficial and fragmented.

Following the intervention, paired-samples t-test results showed a significant improvement in students' conceptual understanding, demonstrating that TE-GIBL positively influenced learning outcomes. Students achieved gains across all genetics domains, with particularly strong improvements in meiosis, gametes, fertilization, gene structure, and Mendelian inheritance. Although understanding of mutation and genetic variation also improved, these concepts remained relatively more challenging, suggesting that some misconceptions are more resistant to change.

Misconception analysis further showed a substantial decline in scientifically inaccurate conceptions and a corresponding increase in complete conceptual understanding. The large effect size indicates that these improvements were not only statistically significant but also educationally meaningful. Qualitative findings from interviews and focus group discussions supported these results, revealing that simulations, animations, visual representations, guided investigations, and collaborative discussions enhanced students' understanding, motivation, confidence, and active participation.

Overall, the findings provide strong evidence that TE-GIBL is an effective instructional approach for promoting conceptual change and reducing misconceptions in genetics. By combining guided inquiry with digital technologies, the approach enables students to engage meaningfully with complex biological concepts rather than relying on memorization. Therefore, TE-GIBL can be recommended as a valuable strategy for teaching genetics and potentially other abstract topics in secondary school biology.

6.2 Recommendations

The findings of this study have practical implications for biology teachers, schools, educational stakeholders, and researchers.

Biology teachers are encouraged to integrate Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) into genetics instruction by using simulations, animations, and other digital resources to teach abstract concepts and by shifting from lecture-based approaches to inquiry-oriented learning. Teachers should also systematically identify and address students' misconceptions, with particular attention to mutation and genetic variation.

Schools, curriculum developers, and educational policymakers should provide adequate technological resources and professional development opportunities to support technology-enhanced inquiry instruction. Secondary school biology curricula should incorporate more inquiry-oriented and technology-supported activities, while schools should promote collaborative professional learning communities among teachers.

Future researchers are encouraged to replicate the study with larger and more diverse samples, investigate long-term retention of genetics concepts, and examine the applicability of TE-GIBL to other difficult biology topics. Further studies should also explore persistent misconceptions related to mutation and genetic variation, employ comparison-group designs, and investigate the role of teachers in mediating the effectiveness of TE-GIBL.

Overall, the findings suggest that combining guided inquiry with digital technologies can promote meaningful conceptual understanding of genetics. Expanding the implementation of such approaches could contribute significantly to improving the quality of secondary school science education.

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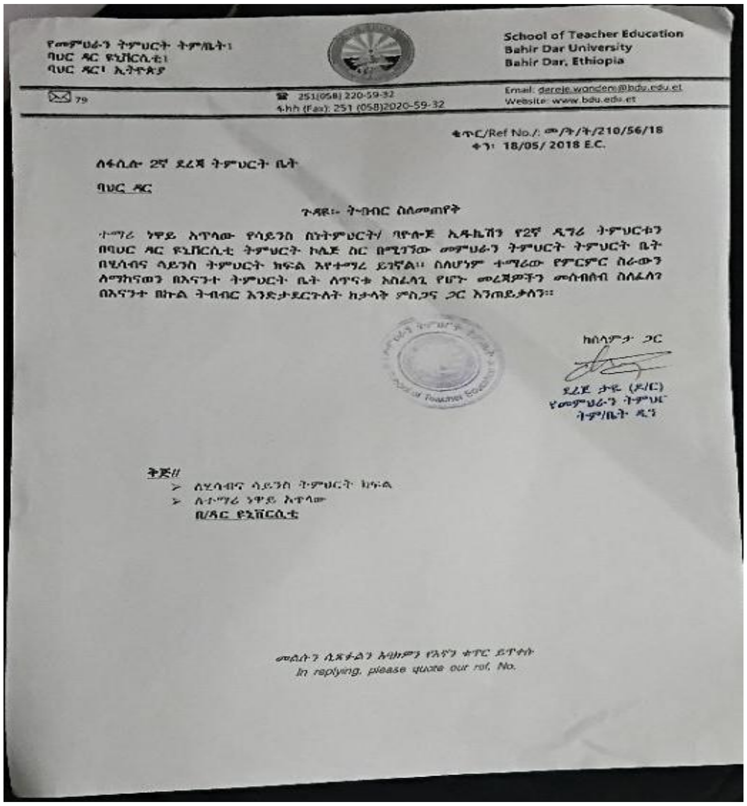
Appendixes



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ከሰላምታ ጋር

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In replying, please quote our ref. No.

Appendix A. Official Research Support Letter from the School of Teacher Education, Bahir Dar University

Appendix B. Researcher Developed Pre-Test on Students' Conceptual Understanding of Genetics (Grade 11)

Pre-Test on Students' Conceptual Understanding of Genetics (Grade 11)

Purpose: This pre-test is designed to assess students' baseline understanding of key genetics concepts covered in Chapter Four of the Grade 11 Biology curriculum. The results will be used for research purposes within a Design-Based Research (DBR) framework and will not affect students' grades.

Instructions to Students

1. Structure of the Test
   - The test consists of two sections:
     - Questions 1–10 are designed to diagnose common misconceptions in genetics.
     - Questions 11–20 are designed to assess your conceptual understanding of genetics concepts.

2. Three-Tier Question Format
    - Each question has three related parts (tiers):
        - Part A (Tier 1): A multiple-choice question about a genetics concept.
        - Part B (Tier 2): A multiple-choice question asking for the reason for your answer in Part A.
        - Part C (Tier 3): A confidence rating where you indicate how sure you are about your answer.

    All three parts of each question are directly related and must be answered.
    - Do not leave any part unanswered.
    - Answer honestly and independently.
    - There are no penalties for incorrect answers.
    - Your responses will help improve teaching and learning in genetics.
    - You are advised to manage your time carefully to complete all questions.

Item Example

Eg1: Content Question

In a monohybrid cross between two heterozygous parents (Aa × Aa), what is the expected phenotypic ratio?

A. 1:1 B. 2:1 ©. 3:1 D. 4:1

Eg. 2: Reasoning

The correct answer is because:

Ⓐ. Alleles segregate equally during gamete formation

B. Dominant alleles are stronger than recessive alleles

C. Recessive alleles disappear after one generation

D. Genes blend together permanently

Eg 3: ☑ Very sure ☐ somewhat sure ☐ Not sure

<u>A. Misconception-Diagnosing Questions (10 Items)</u>

These items are intentionally built around common and well-documented genetics misconceptions.

1: "Genes and chromosomes are the same thing because both are found in the nucleus."
Is the student's statement correct?
A. Yes B. No

1.2: Reason:
A. Genes are whole chromosomes
B. Genes are segments of DNA located on chromosomes
C. Genes exist only during cell division
D. Chromosomes are made only of proteins

1.3: ☐ Very sure ☐ somewhat sure ☐ Not sure

2.1: A dominant allele is one that:
A. Is stronger than a recessive allele B. Is more common in the population
C. Is expressed when a heterozygous genotype is present D. Always comes from the father
2.2: Reason:
A. Dominant traits overpower recessive traits
B. Dominant alleles suppress recessive alleles physically
C. One dominant allele is sufficient for expression
D. Dominance depends on physical strength
2.3: ☐ Very sure ☐ somewhat sure ☐ Not sure

B. Conceptual Understanding Assessing Questions (10 Items)

These items measure correct application, reasoning, and explanation of genetics concepts.

1.1: The main function of a gene is to:
A. Store energy B. Code for a functional product
C. Control cell division only D. Form chromosomes
1.2: Reason:
A. Genes produce traits directly
B. Genes code for proteins or functional RNA
C. Genes act independently of environment
D. Genes are made of proteins
1.3: ☐ Very sure ☐ somewhat sure ☐ Not sure
2.1: An offspring receives alleles from parents because:
A. Alleles blend B. Alleles segregate during meiosis
C. Alleles replicate during fertilization D. Alleles disappear
2.2: Reason:
A. Each gamete carries one allele
B. Gametes carry two alleles
C. Alleles are randomly created
D. Alleles are environmentally determined
2.3: ☐ Very sure ☐ somewhat sure ☐ Not sure

Appendix C. Researcher Developed Post-Test on Students' Conceptual Understanding of Genetics (Grade 11)

Three-Tier Post-Test Subject: Biology – Genetics (Grade 11)

Study Title: Enhancing Grade 11 Students' Conceptual Understanding of Genetics through Technology-Enhanced Guided Inquiry-Based Learning

Instructions to Students

This post-test is designed to assess your understanding of genetics concepts after the instructional intervention.

Questions 1–10 assess areas where **misconceptions** commonly occur.

Questions 11–20 assess your **conceptual understanding** of genetics.

Each question has three related parts:

- ✓ Tier 1: Content answer
- ✓ Tier 2: Reason for your answer
- ✓ Tier 3: Confidence level

Choose one answer for Tier 1, one answer for Tier 2, and indicate your confidence.

Section A: Misconception Diagnosis Items (1–10)

1.1 Which statement is correct about genes?

A. A chromosome is a small part of a gene C. Genes and chromosomes are identical

B. A gene is a section of DNA found on a chromosome D. Genes are proteins inside cells

1.2 Reason:

A. Genes contain many chromosomes

B. Chromosomes are made of proteins only

C. Genes are specific DNA sequences located on chromosomes

D. Genes are produced during cell division

1.3 Confidence level ☐ Very sure ☐ Somewhat sure ☐ Not sure

2.1. Dominant allele is one that:

A. Is more common in a population B. Is stronger physically

C. Is expressed when present in one copy D. Comes only from the father

2.2 Reason:

A. Dominant traits are always common B. One dominant allele can determine phenotype

C. Dominant alleles are larger D. Dominant genes replace recessive genes

2.3 Confidence level ☐ Very sure ☐ Somewhat sure ☐ Not sure

Section B: Conceptual Understanding Items (11–20)

1.1 Genes mainly contain instructions to make:

A. Lipids only B. Functional proteins or RNA C. Chromosomes only D. Water

1.2: Reason

A. Genes store hereditary information used in cell function B. Genes are food reserves

C. Genes are made by ribosomes D. Genes destroy proteins

1.3: Confidence level ☐ Very sure ☐ Somewhat sure ☐ Not sure

2.1 During meiosis, allele pairs:

A. Stay together always B. Separate into different gametes C. Disappear D. Double in number

2.2: Reason:

A. Each gamete receives one allele of a pair B. Gametes receive two alleles

C. Alleles blend D. Separation occurs after fertilization

2.3: Confidence ☐ Very sure ☐ Somewhat sure ☐ Not sure

Appendix D. Researcher Developed Classroom Observation Checklist

Classroom Observation Checklist

Purpose of the Checklist: This observation checklist is designed to assist in evaluating the implementation fidelity, usability, acceptability, and instructional effectiveness of Technology-Enhanced Guided Inquiry-Based Learning (TE-GIBL) in enhancing Grade 11 students' conceptual understanding of genetics

General Information

School **Fasilo secondary school** Date ____________Grade level **11** Section **D**

Number of student present M **28** F **22**Total **50** Subject **Biology**

Period___________

Qualification of the teacher: **MSc**

Lesson topic____

No Activities Description of the observer

No.	Observation Indicators (Title-Aligned)	Not Observed (1)	Partially Observed (2)	Observed (3)	Observer's Remark
1	Technology-enhanced instructional tools (simulations, animations, multimedia) are used according to the lesson plan.				
2	The lesson follows the Guided Inquiry-Based Learning sequence (questioning, exploration, explanation, reflection).				
3	Technology supports students in actively asking questions and engaging in inquiry activities.				
4	Digital resources help students visualize and understand abstract genetics concepts (e.g., meiosis, inheritance, gene expression).				
5	Students demonstrate conceptual understanding through explanations, discussions, or problem-solving tasks.				
6	Technology-enhanced inquiry activities sustain students' attention and interest throughout the lesson.				
7	The teacher facilitates learning by guiding inquiry rather than delivering information through lecture only.				
8	Learning activities encourage higher-order thinking (analysis, reasoning, prediction, or explanation).				
9	Instruction effectively addresses students' misconceptions in genetics.				
10	The TE-GIBL approach is more effective than traditional teaching in supporting students' conceptual understanding.				

Appendix D. Researcher Developed Inquiry Worksheet: DNA and RNA Structure and Function

TE-GIBL Inquiry Worksheet: DNA and RNA Structure and Function

Worksheet 1: Inquiry Activity – Studying DNA

Part A: Engagement Question

If all living organisms contain DNA, why are they different from one another?

Part B: Guided Research Questions

1. What is DNA?

2. How is genetic information stored in DNA?

3. What makes DNA different among organisms?

4. How do genes influence traits?

5. What role do mutations play in variation?

Part C: Explanation Construction

Why do organisms differ if they are all made of DNA?

Worksheet 2: Inquiry Activity Comparing DNA and RNA

Part A: Observed Differences

List at least three differences between DNA and RNA:

1. ____

2. ____

3. ____

Part B: Comparison Table

Feature	DNA	RNA
Full Name		
Definition		
Location in Cell		
Main Function		
Structure		
Type of Sugar		
Nitrogen Bases		
Base Pairing Rules		

Part C: Higher-Order Questions

1. Why is DNA double-stranded while RNA is single-stranded?

2. Why does RNA contain uracil instead of thymine?

3. Why is DNA suitable for long-term information storage but RNA is not?

Part D: Application Question

If a DNA template strand is: TAC GGA TTT. Write the corresponding mRNA strand:

Explain your reasoning:

Part E: Misconception Check (Circle T or F and correct false statements)

1. DNA contains ribose sugar. (T / F)

2. RNA is found only in the nucleus. (T / F)

3. Adenine pairs with thymine in RNA. (T / F)

4. DNA carries hereditary information. (T / F)