# EFFECTS OF INTEGRATED STEM APPROACH TOWARDS **SECONDARY SCHOOL STUDENTS' CRITICAL THINKING** SKILLS AND ACHIEVEMENT IN GENETICS

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# EFFECTS OF INTEGRATED STEM APPROACH TOWARDS SECONDARY SCHOOL STUDENTS' CRITICAL THINKING SKILLS AND ACHIEVEMENT IN GENETICS

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## ABSTRACT

Complex problems in real-life are multidisciplinary. Solving these problems require the ability to think critically and the integration of knowledge from science, technology, engineering, and mathematics (STEM) disciplines. Nevertheless, the observed instructional practices in schools are traditionally-based, and subjects are learnt in isolation which seems not to promote critical thinking skills and academic achievement adequately. Consequently, this study investigated the effects of integrated STEM approach (iSTEMa) on secondary school students' critical thinking skills and achievement in genetics. The study adopted a concurrent mixed method design: the 2x2 factorial and basic qualitative method. Two schools were chosen randomly and assigned as treatment and control group respectively. In the treatment school, 51 students were randomly selected while 49 students were selected from the control school. An instructional material named iSTEMim was prepared for the treatment group. The iSTEMim consists of six instructional elements, and three tasks. The quantitative data were collected using Science Critical Thinking Test, and Genetic Achievement Test. The qualitative data were collected using interviews and observation. Quantitative data were analysed using Multivariate Analysis of Variance (MANOVA), and the qualitative data were analysed thematically. The findings show that there is a significant difference in students' critical thinking skills between the iSTEMa and traditional group. The difference is in favour of the iSTEMa group, indicating that iSTEMa is more effective. The results also indicated that the iSTEMa group perform better than the traditional group in Genetic Achievement Test. It was also found that students' ability did not to influence students' critical thinking skills and genetic achievement. The qualitative data corroborated the quantitative findings. Students were engaged in iSTEMim activities that promoted students' cognitive processes as well as social interaction. This study has implications for policy-makers to encourage the implementation of integrated STEM approaches in schools. It also has implications for teachers' instructional practices in the classroom.

**KESAN PENDEKATAN STEM BERSEPADU TERHADAP KEMAHIRAN BERFIKIR SECARA KRITIS DAN PENCAPAIAN MURID SEKOLAH MENENGAH DALAM GENETIK**


## ABSTRAK

Masalah kompleks dalam kehidupan melibatkan pelbagai disiplin. Penyelesaian masalah ini memerlukan kemahiran berfikir secara kritis dan integrasi pengetahuan daripada bidang sains, teknologi, kejuruteraan dan matematik (STEM). Walau bagaimanapun, amalan pengajaran di sekolah tidak menggalakkan penguasaan kemahiran berfikir secara kritis dan pencapaian yang baik dalam sains. Tambahan, disiplin STEM dipelajari secara berasingan. Oleh itu, kajian ini menyiasat kesan pendekatan STEM Bersepadu (iSTEMa) ke atas kemahiran berfikir secara kritis dan pencapaian murid sekolah menengah dalam genetik. Kajian ini menggunakan kaedah campuran serentak; iaitu reka bentuk faktorial 2x2 dan reka bentuk kualitatif asas. Dua sekolah secara rawak dipilih untuk kumpulan rawatan dan kumpulan kawalan. Lima puluh satu (51) murid telah dipilih secara rawak bagi sekolah rawatan dan 49 dalam sekolah kawalan. Satu bahan pengajaran yang dinamakan iSTEMim, disediakan untuk sekolah rawatan. iSTEMim mempunyai enam elemen pengajaran dan tiga tugasan. Data kuantitatif dikutip menggunakan Ujian Pemikiran Sains secaraKritis dan Ujian Pencapaian Genetik. Data kualitatif dikumpulkan menggunakan temubual dan pemerhatian. Data dianalisis menggunakan MANOVA dan data kuantitatif pula dianalisis secara bertema. Keputusan menunjukkan perbezaan yang signifikan dalam penguasaan kemahiran berfikir secara kritis antara kumpulan rawatan dan kawalan. Keputusan juga menunjukkan perbezaan yang signifikan bagi kumpulan rawatan. Hasil kajian juga mendapati keupayaan murid tidak mempengaruhi penguasaan kemahiran berfikir secara kritis dan juga dalam pencapaian murid dalam genetik. Dapatan daripada data kualitatif menyokong dapatan kuantitatif daripada aspek

kemahiran berfikir secara kritis dan pencapaian murid dalam genetik. Murid terlibat secara aktif dengan aktiviti iSTEMim. Aktiviti ini menggalakkan proses kognitif murid serta interaksi sosial antara murid. Kajian ini mempunyai implikasi terhadap penggubal dasar bagi menggalakkan pelaksanaan pendekatan STEM secara bersepadu di sekolah. Ia juga mempunyai implikasi terhadap amalan pengajaran guru sains di kelas.

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## List of Symbols and Abbreviation

| Abbreviation | Meaning |
|---|---|
| STEM | Science, Technology, Engineering and Mathematics |
| iSTEMa | integrated Science, Technology, Engineering and Mathematics approach |
| OECD | Organisation for Economic Co-operation and Development |
| HOTS | Higher Order Thinking Skills |
| WASSCE | West African Senior School Certificate Examination |
| NGSS | Next Generation Science Standards |
| ADDIE | Analysis, Design, Development, Implementation and Evaluation |
| iSTEMim | integrated Science, Technology, Engineering and Mathematics instructional materials |
| GAT | Genetic Achievement Test |
| WAEC | West African Examination Council |
| NECO | National Examination Council |
| EDP | Engineering Design Process |
| FRN | Federal Republic of Nigeria |
| WGCTA | Watson Glaser Critical Thinking Appraisal |
| CCTT | Cornel Critical thinking Test |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

The primary goal of education in each nation is to help learners develop skills that are appropriate to the needs of society. In today's world, the expectation is that citizens should be able to analyse, assess valuable information, engage in inference, interpretation, explanation, and being able to solve non-routine problems. Corporate organisations and captain of industries have agreed that prospective employees must possess these skills among others to be able to compete favourably in the global market and contribute meaningfully to the society (Casner-Lotto & Barrington, 2006; Howells, 2018; Kivunja, 2014; Saputri, Sajidan, Rinanto, Afandi, & Prasetyanti, 2019). Therefore, global workforce demand of the twenty-first century necessitates the shift in the focus of education from product-based to process-based learning. Educational stakeholders can no longer rely on traditional ways of instruction. This has necessitated the recent educational reforms to meet the yearnings of the society. It is reported that recent reforms in science education are vital tools that are needed to empower individuals with knowledge and relevant skills such as critical thinking skill among others to succeed in the 21st century (Berland, Steingut, & Ko, 2014; Boyer & Crippen, 2014; Kivunja, 2014; Tiruneh, Gu, De Cock, & Elen, 2018). Because of this, there is a conscious search for instructional materials, and approaches that will bring about meaningful learning, and assist students in thinking critically among others.

Educational stakeholders have stressed the importance and urgency of integrated STEM-based instruction to prepare learners for current and future challenges (Alghamdi, 2017; Honey, Pearson, & Schweingruber, 2014; Prinsley & Baranyai, 2015). This may have accounted for the recent international focus on STEM education rhetoric. Therefore, the teacher has a fundamental role in facilitating learning through motivating and employing the right instructional approach to help students acquire these skills and improve their performance in science.

The quality of education that is required in this digital age can only be achieved through a paradigm shift from the traditional model of instruction to innovative instructional strategies that will help students acquire critical thinking skills and integrate knowledge from different sources to solve problems (Goovaerts, De Cock, Struyven, & Dehaene, 2018; Kivunja, 2015). Therefore, the emphasis of classroom instruction now is not about memorisation and rote learning but on meaningful learning, acquisition of relevant skills and the application of these skills and knowledge acquired in the classroom to a novel situation or environment. However, the traditional mode of instruction that emphasises rote learning is predominant in many countries of the world (Niemi, Baker, & Sylvester, 2007; Ofodile & Mankilik, 2015; Saxton et al., 2014; Stapleton, 2011). The situation in Nigeria is not different; science instruction is characterised by memorisation and focus on lower thinking skills (Adesulu, 2016; Okebukola, 2012; Yaki & Babagana, 2016).

Nigerian inherited a system of education from the British, its erstwhile colonial master. After independence in 1960, the science education curriculum in Nigeria has undergone a series of reviews due to prevailing circumstances and the operational needs of the society. The aim is to produce a scientifically literate society that will drive the economy and technological breakthrough of the country.

The importance of building a sound scientific base for the country led to the recommendation of a ratio of 60 (Science); 40 (Arts) in university admission policy in Nigeria (Aidelunuoghene, 2014). It is enshrined in the National Policy on

Education(NPE) that a greater amount of resources shall be dedicated to science and technology at the university level of education (Federal Republic of Nigeria, 2004, P32). Despite the importance placed by the Nigerian government in science and mathematics education, students' achievement in both internal and external examinations in science and mathematics subjects are unsatisfactory (Adeyemi, 2012; Gambari, Yaki, Gana, & Ughovwa, 2013b; Okebukola, 2012).

In view of this, learners in Nigeria are equip with lower thinking skills which are no longer relevant for meaningful living (Abdu-Raheem, 2014; Erinosho, 2013; Olayinka, 2016). Thus creating a gap between the observed instructional practices and the expected skills for the 21$^{st}$-century, which need to be bridged using innovative instructional strategies which may provide meaningful learning (Morgan, Porter, & Zhan, 2011; Ning, 2013). Wagner (2008) warned that those countries that refuse to embrace educational approaches that will prepare students for competition in the global market would be at risk economically and technologically.

In support of this, the Academic Staff Union of Universities (ASUU) in Nigerian universities had urged the Federal Government of Nigeria to reposition the education system at all levels through reforming classroom instruction (Okwoufu, 2014). This will probably enable it to function adequately within the present realities to reflect the values, aspirations, and realities of learning within the context of the global economy. Mundy (2005) advocated for change in the learning environment from traditional to the innovative learning environment and from isolated learning to integrated learning. He also recommended the shift where learners work in isolation to learners working collaboratively.

In this regard, it is important to experiment integrated STEM approach research study in Nigeria because its potentials may provide the Nigerian education system with opportunities which may serve as an impetus for changing the face of classroom instruction. The integrated STEM approach (iSTEMa) may help to produce critical thinkers who will contribute meaningfully to society.

## 1.2 Background of the Study

Integrated instruction offers a meaningful learning environment which helps learners see the connection between knowledge, acquire in the classroom and experiences in real life (Beane, 1995; English, 2016). Discourse about the integration of STEM is built in this broader perspective. Therefore, it is observed that integrated STEM instruction provides the learners with integrated learning experience rather than isolated learning of the STEM disciplines (Bybee, 2013; Lin, Hsiao, Williams, & Chen, 2019). Therefore, the continuing teaching of STEM subjects in isolation has a negative implication for students' science achievement, interest in STEM careers and the acquisition of thinking skills. Therefore, STEM is an instructional approach that eliminates the traditional walls between STEM subjects by integrating them into an instructional paradigm that helps learners to learn in a multidisciplinary environment (Kennedy & Odell, 2014; Morrison, 2006; Roberts, 2012). STEM learning involves the use of knowledge and skills by an individual to solve global, social and personal STEM issues (Bybee, 2010).

Similarly, Stohlmann, Moore, and Roehrig (2012) observed that STEM education involves linking the subjects to real-world problem in the classroom. They further observed that since integrated STEM may always not involve the four STEM discipline, they advocated that engineering should be used as a context for learners to learn STEM concepts. Sanders (2009) defines integrated STEM education as instructional practices between two or more STEM subjects or between a STEM and non-STEM subject.

Moore and Smith (2014) reported that integrated STEM instruction requires students to participate in the engineering design process as a context to integrate science and mathematics concepts. Guzey, Moore, and Morse (2016) accentuate that engineering is a natural link to science and mathematics and is a vital element for meaningful science learning. Therefore, the definition of Moore and Smith (2014) is adopted for this study; students will engage in science through the engineering design process which could enhance their ability to think and genetic achievement

Engineering would provide the learning context where students engage actively in the learning process to acquire skills that could be applied to real-life problem-solving. (Bybee, 2013; Dass, 2015; Kertil & Gurel, 2016; Morrison, 2006). Suffice it to say, in the real world, the domain and knowledge of STEM are regularly integrated into problem-solving and decision making (Herschbach, 2011) contrary to how they are usually taught in the classroom.

Integrated STEM approaches improve motivation to learn, stimulate students' positive interest towards STEM fields as well as improve students' achievement in science (Becker & Park, 2011; Bybee, 2010; Laboy-Rush, 2011). Similarly, It is reported that an integrated STEM approach enhanced students’ critical thinking, innovative and problem-solving skills (Karbalaei, 2012; Morrison, 2006; Shah, 2010; Thomas, 2013). In support of this, it is observed that the specific skills that can be required to build a vibrant economy in the twenty-first century are embodied in the integrated STEM-based education which could stir innovation (Langdon, McKittrick, Beede, Khan, & Doms, 2011).

Individuals are regularly challenged with information and problems that require them to interpret, analyse, evaluate and take a decision, especially in the 21st century. The ability to do that effectively depends on the integration of knowledge from different sources, mainly from STEM disciplines. Given this, scholars advocated the need to instruct students with the integrated STEM education because of its relevance to successful living and problem-solving (Corlu, Capraro, & Capraro, 2014; Lynch, Behrend, Burton, & Means, 2013; Mahoney, 2010; Osman & Saat, 2014). Thus, subject-specific learning has an inhibiting consequence on learning, because students would lack the skills to integrate knowledge from different disciplines to solve real-life problems (Beane, 2009; Treacy & O'Donoghue, 2014). Therefore, the need to experiment with integrated STEM-based instruction.

Critical thinking skill is considered an indispensable skill that should be inculcated into the future generation so that they can successfully thrive in the dynamics of the 21st century. Hence, it is highlighted as an essential goal of education globally (Deakin, 2014; Facione, 2011; Federal Republic of Nigeria, 2004, P32; Tiruneh et al., 2018). In support of this assertion, others observed that the import of critical thinking involves viewing problems from a different perspective and relating learning across different subjects and discipline (P21, 2015). This implies the ability to integrate knowledge from different disciplines to solve the non-routine problem. Integrated STEM instruction could help learners think critically and improve students' achievement because it emphasises the engagement of students' higher cognitive abilities through defining problem, generation of ideas and collaboration

Students' ability is an important factor for consideration with regards to students learning of science because it influences students' learning differently based on the instructional approach or environment (Karpudewan & Chong, 2017; Prayitno, Suciati, & Titikusumawati, 2019). Researchers have adopted several instructional strategies to examine the effects of students' ability towards science learning, and the results are inconclusive (Chen, Huang, & Chou, 2016; Cheng, Lam, & Chan, 2008; Gambari, James, & Olumorin, 2013a; Han, Capraro, & Capraro, 2014; Kuo, Tuan, & Chin, 2018; Thalib, Corebima, & Ghofur, 2017). Instructional approaches that are learner-centred have been advocated to provide learning equity among student with different ability (Prayitno et al., 2019).

Science and mathematics achievement gap are identified between high and low achievers especially in the traditional instructional environment where high achievers perform better than low achievers (Gambari et al., 2013a; Han et al., 2014). This achievement gap may minimise the educational and economic prospects of low and medium ability achievers (Lin & Lin, 2016; Meyer & Crawford, 2015). Consequently, bridging this gap could require the use of learning approaches that could address diverse students' ability through active engagement such as STEM-based approaches. Therefore, there is a need to consider students' ability as a moderating variable by examining how students' ability (high and low) could influence students critical thinking skills and learning of genetics.

## 1.3 Statement of Problem

The need to use approaches that enhance critical thinking skills and problem-solving have been advocated (Cheng, 2011; Prinsley & Baranyai, 2015; Sada, Mohd, Adnan, & Yusri, 2016; Tiruneh et al., 2018). Because the importance of critical thinking is highlighted by the fact that employers in the 21st-century are looking for employees who are lifelong learners and can think critically (Bevins, Carter, Jones, Moye, & Ritz, 2012; Levin-Goldberg, 2012). Therefore, the quality of life of an individual is closely associated with his/her ability to think critically. Problems encountered in real-life are multifaced with several dimensions, these problems could only be solved by the ability to infer, evaluate, deduce, interpret, and recognise assumptions (Atabaki, Keshtiaray,

& Yarmohammadian, 2015). Karbalaei (2012) reported that teaching and learning that enhance critical thinking skills would enhance students' achievement. Hence, the justification of the focus on critical thinking skills; inference, recognising assumptions, deduction, interpretation, and evaluation in this study.

However, the instructional approaches employed by teachers has not adequately assist learners in acquiring critical thinking skills, and this is not peculiar to one country in the world (Egege, & Kutieleh, 2004; Paul 2011). In many countries, it has been reported that students' ability to think critically is low (Demiral, 2018; Stapleton, 2011; Willingham, 2007). This implies that students' ability to infer, deduce, analyse interpret, explain and conclude is unsatisfactory. In Nigeria, students exhibit a low level of critical thinking skills and students' achievement in science continue to dwindle (Ezeudu, Ofoegbu, & Anyaegbunnam, 2013; Pitan & Adedeji, 2012; Sada et al., 2016; Salami, 2013). Although, studies linking critical thinking skills and students' achievement have been reported in the literature (Forawi, 2016; Yuan, Liao, & Wang, 2014; Zhou, Huang, & Tian, 2013). Nonetheless, it is observed that students' ability to think critically continue to be unsatisfactory (Forawi, 2016; Pitan & Adedeji, 2012; Sada et al., 2016). This could also have implications for students' learning and academic achievement.

Consequently, to resolve these problems of students' inability to think and unsatisfactory achievement in science, science education researchers have adopted several techniques in classroom instruction and have yielded significant students' achievement (English & King, 2015; Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005; Kertil & Gurel, 2016).

Some of the strategies employed includes; Inquiry-based learning (Dolan & Grady, 2010; Kivunja, 2015; Ku, Ho, Hau, & Lai, 2014), interdisciplinary strategies like design-based science learning have also been linked to have positive effects on critical thinking and achievement (Duran & Sendag, 2012; Fortus et al., 2005; Wells, 2016; Zhou et al., 2013). Nevertheless, students' lack of critical thinking skills has persisted (Chukwuyenum, 2013; Sada et al., 2016). Hence the need to try other relevant instructional strategies such as integrated STEM instruction. There is a consensus among researchers that the STEM approach has the potential to help learners acquire critical thinking skills and improved achievement (Herschbach, 2011; Kertil & Gurel, 2016; Wells, 2016).

Watson and Glaser's subskills (inference, recognising assumption, deduction, interpretation and evaluation) are adopted in this study because firstly, these subskills also appear in others researchers classification of critical thinking skills, (Ennis & Millman, 1985; Liu, Frankel, & Roohr, 2014). Secondly the psychometric properties of Watson-Glaser's critical thinking skill classification, it is seen as the best-known critical thinking test and the most widely used (Liu et al., 2014; Piaw, 2010; Zulmaulida, Wahyudin, & Dahlan, 2018). Thirdly, it has been adopted for used among senior secondary school students by researchers (Alrubai, 2014; Piaw, 2010). For example, WGCTA was designed for grade 9 or above (Watson & Glaser, 1980). However, Woehlke (1985) argued that the WGCTA reading level was for grade 9, but the cognitive skills were higher than grade 9. Therefore, the researcher thinks its structure and definition of critical thinking skills were more appropriate for this study because the study focused on grade 11.

In most countries, and specifically Nigeria, the curriculum is traditionally subject specific where STEM disciplines are taught in isolation (Dare, Ellis, & Roehrig, 2018; Saxton et al., 2014; Wang, Moore, Roehrig, & Park, 2011). Although the subjects are taught in silos, problem-solving by professional in real-life blurs the lines between the disciplines. Furthermore, many teachers may encounter difficulty to implement integrated instruction; they cannot translate general research studies into instructional practices (Ezeudu et al., 2013; Saxton et al., 2014). Literature has revealed some gaps on insufficient instructional materials in implementing integrated STEM because it is relatively new (Damilola, Adebimbo, & Alaba, 2016; Kertil & Gurel, 2016; Wang et al., 2011). The few available ones are from other countries and do not fit the cultural and instructional content of the science syllabus in Nigeria. Hence, the need to prepare an instructional material to help teachers implement integrated STEM approach (iSTEMa).

Twenty-century's evolving development in genetics such as bioengineering and genomic advances makes genetic teaching and learning very important. This to prepare individuals to be citizens that are informed, can make a good decision and contribute meaningfully to the discourse on genetic advances (Duncan & Tseng, 2010; Freidenreich, Duncan, & Shea, 2011). However, learning difficulties in genetics at secondary school level of education have been reported (Danmole & Lameed, 2014; Haambokoma, 2007; Mills Shaw, Van Horne, Zhang, & Boughman, 2008; Tsui & Treagust, 2002; West African Examination Council, 2007). These learning difficulties have led to the unsatisfactory achievement of students in genetics at all levels of education, especially at the secondary school level (Atilla, 2012; Danmole & Lameed, 2014; Dikmenli, 2010). Causes of learning difficulties in genetics include: teacher centred instructional strategies (Duncan & Reiser, 2007; Haambokoma, 2007), abstract nature of genetics because most genetic concepts and processes are cellular in nature (Atilla, 2012; Mthethwa-Kunene, Onwu, & de Villiers, 2015), genetics is multidisciplinary in nature, involving some aspects of mathematical probability (Atilla, 2012; Tekkaya, Ozkan, & Sunkur, 2001). Therefore, the use of a multidisciplinary approach such as STEM education may be appropriate for its teaching and learning.

Scholars have advocated that critical thinking skills be taught in a context or subject-specific domain (Santos, 2016; Tiruneh, De Cock, Weldeslassie, Elen, & Janssen, 2017; Zhou et al., 2013) and would not be easy because the procedures for helping learners develop critical thinking skills differ from one discipline to the other (Tiruneh et al., 2017). Therefore, critical thinking is explicitly integrated into the learning of genetics in this study with the hope that critical thinking will assist in enhancing meaningful learning of genetics.

Previous literature has reported a connection between critical thinking skills, and students' achievement (Akyol, Sungur, & Tekkaya, 2010; Ghanizadeh, 2016; Karbalaei, 2012; Lazarowitz & Naim, 2012). Karbalaei (2012) in his study of critical thinking and academic achievement, found that critical thinking development among learners improves academic achievement. This is because critical thinking tasks help to deepen learners' understanding. Akyol et al. (2010) opined that higher order thinking tasks improve students' achievement in science. Therefore, since the development of critical thinking skills enhances students' achievement, it could be inferred that deficiency in critical thinking skills will lead to poor academic achievement. However, teachers believe that task requiring the development of thinking skills such as critical thinking is not appropriate for low achievers (Yu, She, & Lee, 2010).

Students' learning outcomes have been linked to students' academic ability (Gambari et al., 2013a; Karademİr & Uçak, 2009; Yu et al., 2010). However, this may depend on several factors among which the instructional approach and the quality of learning appear prominently (Karademİr & Uçak, 2009; Toomela, Kikas, & Mõttus, 2006). However, a gap exists as observed by Zohar and Peled (2008) who found that, teachers believe that engaging low achieving in reasoning or critical thinking is not appropriate because of their academic capabilities. It is believed that task requiring higher cognitive processing is only appropriate for high achievers. Hence, the need to consider students ability as a moderating variable to find out, if ability levels affect students' ability to think critically when exposed to the integrated STEM approach to instruction. The statement of the problem is summarised as presented in Figure 1.1

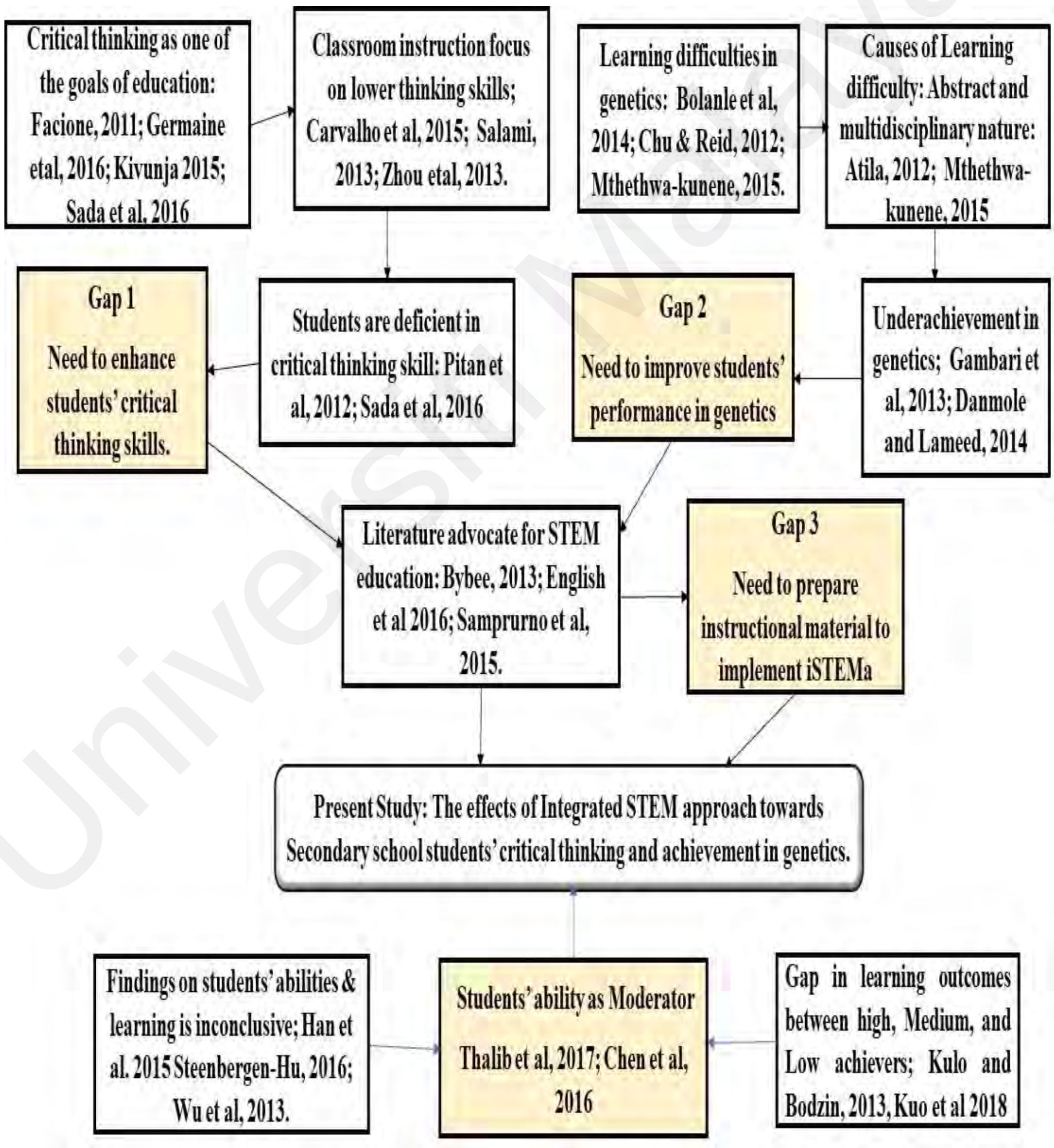


*Figure 1.1. Summary of the Problem*

The result of this study could contribute to the scope of knowledge on integrated STEM instructional approach and students' critical thinking skills and achievement. Thus, this study seeks to investigate the effects of integrated STEM approach towards secondary school students' critical thinking skills and achievement in genetics.

## 1.4 Objectives of the Study

This study aims to investigate the effects of integrated STEM approach (iSTEMa) towards secondary school students' critical thinking skills and achievement in genetics. Therefore, an integrated STEM instructional material (iSTEMim) was prepared to implement the iSTEMa. Specifically, this research study seeks to achieve the following research objectives:

1. To determine the elements to be embedded in iSTEMim that could enhance senior secondary school students' critical thinking skills and achievement in genetics
2. a) To investigate the effectiveness of the iSTEMa on senior secondary school students' critical thinking skills.

   b) To explore how iSTEMa enhances critical thinking skills among senior secondary school students.
3. a) To investigate the effectiveness of the iSTEMa on senior secondary school students' achievement in genetic concepts.

   b) To explore how iSTEMa improves genetic achievement among senior secondary school students.
4. To determine the interaction effects between students' ability (high, and low) and instructional approach (iSTEMa and traditional approach) on senior secondary school students' critical thinking skills

5. To investigate the interaction effects between students' ability ((high, and low) and instructional approach (iSTEMa and traditional approach) on senior secondary school students' achievement in genetics
6. To describe the learning experiences of the senior secondary school students upon iSTEMim to learn.

## 1.5 Research Questions

To guide this study, the following research questions were stated;

1. What are the elements embedded in iSTEMim that could promote senior secondary school students' critical thinking skills and genetic achievement?
2. a) Is there any significant mean difference in critical thinking skills between senior secondary school students that learn with iSTEMa (experimental group) and those who learn using the traditional method (control group)?

   b) How does the iSTEMa enhance critical thinking skills among senior secondary school students?
3. a) Is there any significant mean difference in genetic achievement between senior secondary school students that learn with iSTEMa and those who learn using the traditional method?

   b) How does the iSTEMa improve genetic achievement among senior secondary school students
4. Are there any significant interaction effects between students' ability (high, and low) and instructional approach (iSTEMa and traditional approach) on senior secondary school students' critical thinking skills?
5. Are there any significant interaction effects between students' ability (high, and low) and instructional approach (iSTEMa and traditional approach) on senior secondary school students' achievement in genetics?

6. What are the learning experiences of the senior secondary school students upon using iSTEMim to learn?

## 1.6 Research Hypotheses

The null hypotheses were formulated to test the quantitative research questions. This implies that research question 1 and 6 cannot be tested quantitatively however, research question 2a, 3a, 4, 5 can be tested quatitatively. The formulated research hypotheses are as follows:

1. There is no significant difference in the critical thinking skills between senior secondary school students that learn with iSTEMa and those who learn using the traditional method.
2. There will be no significant difference in the achievement of senior secondary school students' in genetic concepts between senior secondary school students that learn with iSTEMa and those who learn using the traditional method.
3. There are no significant interaction effects between students' ability (high, and low) and instructional approach (iSTEMa and traditional approach) on senior secondary school students' critical thinking skills.
4. There are no significant interaction effects between students' ability (high, and low) and instructional approach (iSTEMa and traditional approach) on senior secondary school students' achievement in genetics.

## 1.7 The Rationale of the Study

There are observed issues related to science education instruction in Nigeria at all levels of education most importantly at the secondary school level, that prompted the researcher to carry out this research study. Some of these issues include:

The achievement gap in science education in Nigeria: in 2014, United Nations Educational, Scientific and Cultural Organization (UNESCO) in an article, "Teaching without learning in Nigerian schools," observed that Nigeria is one of the 37 countries in the world where learning has deserted schools (Punch, 2014). One of the primary reasons given by UNESCO on why teaching has deserted Nigerian schools is poor quality teaching which is predominantly didactic. They further remarked that this had hampered learning in Nigeria, resulting in dwindling achievement in science subjects. Given this dwindling achievement, UNESCO has agreed to partner with Nigeria to address the ugly trends in mathematics and science achievement at the secondary school level through promoting teaching and learning through the use of learner-centred approaches and by establishing a STEM education project (Nnabugwu, 2013). Hence, the need to improve students' achievement in biology using integrated STEM approach.

The current Nigerian education system is performing below expectation because the traditional model of instruction used by science teachers has failed to prepare students adequately. Because of biology instruction is isolated from other science subjects and does not engage their cognitive abilities effectively. In real-life problem-solving, these disciplines are not isolated but integrated to solve problems. Hence, schools should embrace integrated instructional approaches, so that classroom instruction is relevant to real-life problem-solving. Programme for International Students Assessment (PISA) assessment of critical thinking skills and problem-solving skills outcome clearly shows that countries with better achievement in these skills had better Gross Domestic Products (GDP) and by implication better economic growth (Hanushek & Wößmann, 2008). As important as critical thinking skills are for economic growth. However, it was reported earlier that Nigerian graduates are deficient in critical thinking skills. Thus, this gap could be bridged by employing the integrated STEM education approach to enhance critical thinking skills.

Lack of interest by students can be seen in the inability of the Nigerian public university to achieve the 60:40 proportion in admission for STEM-based courses and others respectively. This could be attributed to lack of motivation to learn science because of lack of conducive learning environment and the use of approaches that do not help learners see the connection between what is learned in the classroom and real-life. This trend has implication for human resources development in STEM careers, and this portrays threat for the country quest for technological and economic development as well as achieving her vision 20: 2020 (among the top twenty economies by the year 2020)

Several studies have linked integrated STEM to students' achievement and interest in science. However, most of these researches are domesticated abroad (Bybee, 2010; English, King, & Smeed, 2016; Han et al., 2014). Hence, the motivation of the researcher to link integrated STEM to students' development of critical thinking in Nigeria. The role of the teacher has changed from the giver of knowledge to the facilitator of the learning process, on the other hand, the students' role has also changed from passive receivers of knowledge to one who engages in the construction of knowledge on their own. Hence the need to experiment iSTEMa who could create the environment for these new roles

Taking these concerns and putting them into perspective, the researcher considers it essential to carry out this research study in Nigeria. The study may be considered timely because STEM discourse is one of the current reforms for meaningful learning for the 21st century. This study adopted a mixed method research approach to investigate an integrated STEM approach and the acquisition of critical thinking skills among senior secondary school students in biology.

## 1.8 The Significance of the Study

One of the reforms in science education across the world is focused on integrated STEM approach to help learners acquire thinking skills for successful living and national development. It is hoped that the finding from the study would provide useful data and insight into the instructional process using iSTEMa.

Literature revealed that STEM education is relatively an innovative approach (Saraç, 2018). Teachers may not have the expertise to implement the approach, and there are no instructional materials in Nigeria to implement iSTEMa. This study involves the preparation of iSTEMim this will guide and provide the teachers with the instructional knowledge to implement iSTEMa. Therefore, the instructional material developed in this study could serve as a guide for teachers to develop STEM instructional materials in other science concepts.

Theoretically, this study could provide an understanding of how students develop critical thinking skills; this could be valuable to educators especially in designing their instruction to enhance students' critical thinking skills. The findings could be beneficial to science educators in improving their instructional knowledge.

The investigation of integrated STEM approach on critical thinking among high, and low achievers will yield valuable data that will be suitable and important to students and teachers. Teachers will be better prepared to implement integrated STEM approach to instruction especially in bridging the gap between high, and low achievers as well as helping low achievers cope with a higher cognitive task.

From a broad review of literature, no research study was located related to integrated STEM approach on students' development of critical thinking skills and achievement in genetics (Thibaut et al., 2018a). Given that, research on integrated STEM instruction is also relatively new. Therefore, the finding of the study might provide valuable data that could motivate pre-service teachers' institution that includes iSTEMa in their curriculum and taught as an approach to instruction

Teachers have found genetics to be one of the difficult concepts to teach in science, and students continue to experience learning difficulties in genetics leading to students' underachievement in genetics. The finding of this study could help students overcome the learning difficulties in genetics and will motivate teachers to apply the approach to teaching other complex science concepts.

One of the instruments for data collection (science critical thinking test) was adopted and adapted by the researcher to measure students' critical thinking abilities. The instrument could provide insight to future researchers who may want to develop or prepare a similar instrument.

### 1.9 The Scope, and Delimitation of the Study

This study was limited to the effects of integrated STEM approach on senior secondary school students' critical thinking skills and achievement in genetics. The study was limited to senior secondary schools or upper secondary schools which was the target population. The geographical scope was limited to Niger State, Nigeria. The samples of this research study were restricted to senior secondary school class science students (year 15). Therefore, the findings from the sample can only be generalised to the population. The study reviewed the literature of high, medium and low achievers but the study is limited to only high, and low achievers. The medium achievers were not included in the study because the study is a 2 x 2 factorial design, focusing on high and low achievers.

### 1.10 Limitation of the Research

This study is similar to any other study has limitations. These are issues that could impact the interpretation of the results. The approach is a relatively new approach to instruction (Osman & Saat, 2014; Roberts, 2012). Since it is an innovative approach, this may create a sense of frustration among the students which may influence the findings of the study. Therefore, an iSTEMa instructional material was developed to guide the students and the facilitator during implementation. Furthermore, the researcher trained the teacher on how to implement the approach, and the students were also given orientation on how to learn using iSTEMa.

Another limitation of this study is research mortality; this is the case where some of the participants may drop out for reasons beyond their control, and that could impact the outcome of the research. Therefore, to deal with this situation, The researcher recruited a large number of sample size; 108 students. Hence, 8 students drop from the study.

The teacher who participated in this study could impose another critical limitation. The teacher was an experienced science teacher who teaches biology, and he was trained in the implementation of the approach. However, the teacher was not assessed to determine whether they are qualified to implement the approach. To overcome this limitation, there was regular briefing between the researcher and the participating teachers and suggestions were given on how to improve the learning facilitation and interaction. During observation data collection, video recording was not allowed; therefore, the researcher uses field notes.

The population of this study were federal government colleges in Niger state. The knowledge and attributes of the students could be unique. Therefore, generalisation may not apply to other types of schools.

## 1.11 Definition of Terms

**Integrated STEM Approach (iSTEMa):** Is an approach to instruction where students engage in science (genetic) learning using the engineering design process as a context. In this study, genetics was the learning content while the engineering design process serves a complementary role

**iSTEMa instructional material** (**iSTEMim):** This is an instructional material that is designed based on the ADDIE model to implement a STEM approach (iSTEMa). This instructional material is made up of learning objectives, instructional elements, phases, and tasks.

**Traditional Teaching Method:** It refers to a teacher centred instructional process where teachers present the learning content to students in a conventional way. The students are passive listeners and are rarely engaged in the instructional process

**iSTEMa Phases:** This is an iterative cycle adapted from the Engineering design process (EDP) which serve as a context to learn genetics through the integration of genetic and mathematics concepts to solving a genetic design problem. The phases include; the engaging problem, generation of ideas, designing a solution, evaluating and improving and communication of findings.

**iSTEMa Elements:** These are elements adopted from literature and embedded in the iSTEMim with a view that these elements could enhance students' critical thinking skills and active engagement. The elements include; an open-ended problem, questioning, real-world problem, hands-on activities, minds-on activities, and inquiry.

**Critical Thinking Skills:** These are an individual's cognitive processing skills of inference, recognising assumption, deduction interpretation and evaluating arguments. Therefore, it is the cognitive ability to make inference, interpretation, evaluation of arguments, deduction and recognising assumption of Nigerian senior secondary school students measured with the Critical Thinking Test.

**Genetic Achievement Test;** are standardised questions on the genetics concepts; Mendel's laws, probability and terminology adapted and adopted from the West African Examination Council (WAEC) and National examination council (NECO).

**Ability Level;** This is the grouping of students based on their aggregate score in science over a session into high and low ability; high achievers are students whose aggregate score was 70% and above (≥ 60%) while low achievers were students who score less than 60 % (≤ 59%)

## 1.12 Chapter Summary

In this chapter, the researcher highlighted the introduction and background of the study. A gap was established between the observed educational practices and the expected knowledge and skills needed. The gap could be bridged using iSTEMa to enhance the development of critical thinking skills and achievement in genetics among senior secondary school students in Nigeria. Given the objectives of the study, research questions were stated. The rationale of the study and the significance of the study were highlighted.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

The study explores integrated STEM approach on students' ability to think critically among secondary school students. Therefore, this chapter focuses on the review of related literature on this study. The review was done to gather relevant and useful information that will give insights to build a sound theoretical, conceptual and methodological framework. Relevant literature was reviewed under the following subheadings; Nigerian education system and science instruction, curriculum integration, STEM education, integrated STEM education, STEM-based instruction, and students' achievement, critical thinking skills, students' academic ability, genetics and summary of the chapter.

## 2.2 Nigerian Education System and Science Instruction

Nigerian policymakers recognise the efficacy of education as a potent tool for national development, hence, adjusted her philosophy of education to develop learners that will fit into the dynamic nature of the modern economy (Federal Republic of Nigeria, 2004, P32). "*Government shall popularise the study of sciences and the production of an adequate number of scientists to inspire and support national development"* (Federal Republic of Nigeria, 2004, P32). One of the national goals of education that is derived from the philosophy of Nigerian education is *for learners to acquire appropriate skills and the development of the cognitive, physical, other competencies, and abilities for the individual to contribute meaningfully to the development of the society* (Federal Republic of Nigeria, 2004, P32)

The policy statements look very laudable. Several researchers reported that the National Policy on Education in Nigeria is well designed to equip the future generation with fundamental skills to drive the economy, but the policies are not implemented to yield the desired results (Dike, 2009; Ndagi, 2014; Obanya, 2004). This is obvious because graduates have paper qualification and certificates, but they lack the requisite skills to compete favourably in the global market (Pitan & Adedeji, 2012).

In the Nigerian education system, the learning of science is recommended for all levels of education because it is the gateway to achieving sustainable development (Udeani & Adeyemo, 2011; Usman, 2010). It is recommended that science should be taught in an explorative manner characterised by an investigation, experimentation and hands-on activities. However, there is the poor implementation of the curriculum. Some of the problems discovered for poor implementation of the curriculum include; the use of traditional instructional strategies, reluctance to use innovative instructional strategies and lack of adequate instructional materials (Danmole & Lameed, 2014; Ezenwa, 2005; Kola, 2013; Lammi & Denson, 2013; Olayinka, 2016; Umar, 2011; Yaki & Babagana, 2016). The situation is further compounded by the nature of the curriculum which is subject specific with artificial boundaries created between individual STEM subjects.

Given the proceeding, the members of the partnership of 21st-century skills observed that education is obsolete in its strategies for teaching and learning. They called for the need for an instructional process to develop 21st-century skills such as critical thinking skills among others (Symonds, Schwartz, & Ferguson, 2011). To achieving this, teaching and learning should be interdisciplinary or curriculum integration among subjects with an emphasis on hands-on activities and exploration (Morrison, 2006; Symonds et al., 2011; Wagner, 2008).

## 2.3 Curriculum Integration

The major support for integrated instruction and curriculum lies in the progressive educational philosophy, who believe that what happens in the school is not similar to what is happening in the real world and has no meaning to the child (Dewey, 1902; Park, 2008). Wang et al. (2011) reported that problems encountered in real life are multidisciplinary and to solve the problem requires the integration of multiple STEM concepts and processes. The integrated instructional goal is derived from the assertion or arguments that problems in the real world are not isolated into separate disciplines (Beane, 1995; Wang, 2012). Instruction becomes integrated when instructional contents from more than one discipline or subject are deliberately embraced. It is the conscious application of the methodology of more than one subject to a problem or theme (Etim, 2005). Proponents of the integrated instruction argue that learning discipline in isolation will negatively affect the learners' morale and motivation. These advocates observed that integrated instruction should begin with a problem, issue or concern, working to solve the problem will deepen learners understanding and help them communicate their findings to the world (Beane, 1995). It emphasises the active construction of meaning rather than passive assimilation of knowledge.

Integrated instruction has been classified according to their increasing level of integration and how concepts and skills are integrated (Vasquez, Sneider, & Comer, 2013). Their classification includes disciplinary, multidisciplinary, and interdisciplinary and transdisciplinary:

1. Disciplinary: This teaching and learning concepts and skills in individual subjects. An example would be learning STEM subjects in isolation

2. Multidisciplinary: teaching and learning of concepts and skills in isolation in each discipline around a common theme. This implies that disciplinary boundaries are preserved (Ntemngwa & Oliver, 2018)

3. Interdisciplinary: relevant concepts and skills are learned from two or more discipline that will help deepen students understanding and enhance skills development

4. Transdisciplinary: an instructional process that involves learning concepts and skills from two or more discipline independently and is applied to building a project and in the process, students' learning experience could be enhanced.

Based on these definitions, integrated STEM education could be seen as an interdisciplinary approach because integrated STEM education is teaching and learning that explore two or more STEM subjects to achieve a learning goal (Sanders, 2009). It is advocated that the classroom should be characterised by social, personal and global related issues as well as integrating the complementary components of STEM (Bybee, 2010). Several studies have advocated for interdisciplinary STEM integration at the secondary school level of education (Corlu et al., 2014; Kertil & Gurel, 2016; Roehrig, Moore, Wang, & Park, 2012). This study focused on secondary school students.

### 2.3.1 STEM Education

The STEM education acronym was coined by Judith Ramley, the director of the National Science Foundation (NSF) Education and Human Resource division 2001 – 2004 (National Science Foundation, 2012). Before this time the National Science Foundation used the acronym SMET (science, mathematics, engineering, and technology). Some other researchers reported that through the National Science

Foundation (NSF) STEM education acquired its name and had gained prominence all over the world for its perceived potential to improve K-12 education (Salinger & Zuga, 2009; Williams, 2011)

The perusal of literature has clearly shown that STEM and STEM education are used interchangeably (Bybee, 2010; Ntemngwa & Oliver, 2018). However, a few literature has provided differences between the two; STEM is an acronym for Science, technology, engineering and Mathematics, while STEM education is an instructional process or pedagogical concept in the science, technology, engineering and mathematics disciplines (Gonzalez & Kuenzi, 2012; Kennedy & Odell, 2014; Meyrick, 2011). Basham and Marino (2013) accentuate that STEM education as an instructional process to exploit the mutual interrelationship between the four STEM subjects or fields. The co-dependence and interrelated nature of STEM fields in real-life give rise to integrated STEM approach.

An important goal of STEM education is to nurture a society that is STEM literate with knowledge and ability to identify a problem, provide a possible solution, solve the problem and communicate their findings that are evidence-based (Erkens, Schimmer, & Vagle, 2019). If students can exhibit skills, attitudes, and knowledge of STEM disciplines that would minimize the problem of workforce needs in the evolving nature of the global economy (Kennedy & Odell, 2014). In view of the importance of STEM education, during the International Council of Association for Science Education (ICASE) world conference where 34 countries were represented; a declaration called the Kuching declaration was made calling on researchers and other stakeholders in education to consider as a matter of urgency the need to equip students with skills to be global citizens (ICASE, 2013).

STEM education is a vital element of economic success because it has the potential to enhance life-long learning (Herschbach, 2011; Stohlmann, Moore, McClelland, & Roehrig, 2011). Schlechty (2011) observed that STEM integration is the foundation for more in-depth learning in STEM education. Therefore, this underscores the need for research on Integrated STEM education especially at the secondary school level of education.

## 2.4 Integrated STEM Education

Integrated instruction has been investigated for decades by science education scholars (Becker & Park, 2011; Fortus et al., 2005; Roth, 1992; Satchwell & Loepp, 2002; Treacy & O'Donoghue, 2014). What is relatively new is the integration of STEM as an integrated approach to instruction. The benefits of Integrated STEM have been highlighted to include; improved students' achievement and interest in science and mathematics (Fantz & Grant, 2013; Gallant, 2010; Shahali, Halim, Rasul, Osman, & Zulkifeli, 2017; Stohlmann et al., 2012). Researchers have reported that complex learning task in science could be taught successfully through integrated STEM education which could grant the students' real-world learning experience that will accrue in the acquisition of problem-solving skills, critical and analytical thinking skills (Brown, Brown, Reardon, & Merrill, 2011; Patel, 2010).

Although advocates of the implementation of an integrated approach to instruction believe that traditional teaching of subjects in silos does not help students gained meaningful understanding and identify the connection between individual disciplines. However,  the efforts to change the traditional curriculum in favour of integrated instruction might be resisted because the curriculum is always deeply entrenched in the tradition of the people and change could be resisted (Williams, 2011). Furthermore, scholars have a reservation and contrary opinion about integrated STEM-based instruction. They argued firstly that STEM disciplines are complex and classroom teachers are not trained and equipped for STEM integrated instruction. Secondly, the disciplines of STEM are unique, and there is no STEM discipline in practice (Lederman & Lederman, 2013). Therefore, there is the need to establish how integrated STEM approach looks like in the classroom.

Although there is a consensus on the role of the teacher in a STEM classroom as a facilitator while learning is student-centred. However, there is disagreement among scholars about what qualifies STEM education instruction in the classroom (Brown, 2012 & Honey et al. 2014). Garnering from literature, integrated STEM education could be in any of these forms;

- Learning of a small content area of one STEM discipline in the context of one or more STEM discipline; learning science in the context of engineering, technology or both (Honey et al., 2014; Kertil & Gurel, 2016; Roehrig et al., 2012)
- integrated STEM education should include engineering (Dailey, 2017; Shahali et al., 2017); it must involve authentic or real-world problem
- Learning content from two STEM areas; example learning the contents of engineering and mathematics (Kertil & Gurel, 2016). Learning content integrated among the four STEM areas (Brown et al., 2011)
- Organising instruction around a theme or big idea where a relevant portion of STEM areas are integrated (Bybee, 2010)

This study will seek to focus on learning in a given area of science (genetics) in the context of engineering and mathematics (Honey et al., 2014; Kertil & Gurel, 2016; Moore & Smith, 2014)

Given the importance of STEM instruction, little research on integrated STEM approach and students' acquisition of critical thinking have been reported. Lack of adequate STEM education reforms and implementation will have a massive implication on students' learning.

### 2.4.1 Features of Integrated STEM Instruction

There are no widely agreed features of integrating STEM instruction (Dennis & O'Hair, 2010). However, there is a consensus among researchers on some common features or characteristics of integrated instruction (Edwards, 2014; Stohlmann et al., 2012). Some researchers advocated that integrated STEM instructional should be contextualised based on specific criteria; design-based learning, engineering design process, inquiry-based instruction, content and context-based learning (Kertil & Gurel, 2016; Sampurno, Sari, & Wijaya, 2015; Treacy & O'Donoghue, 2014). While others advocate for problem-based learning and project-based learning (Ntemngwa & Oliver, 2018; Robinson, Dailey, Hughes, & Cotabish, 2014)

It was observed that both the engineering design process and scientific inquiry should be given equal emphasis in science instruction in NGSS because of their critical roles in enhancing the acquisition of thinking skills (Reeve, 2013). It is important to note that both scientific inquiry and engineering design process are driven by questions based on real-life. The features of integrated instruction include; a) hands-on learning, b) learner-centred activities, c) 21$^{st}$-century skills, d) focus on a real-life problem. Others include; e) constructivist-based, f) experiential learning, and g) teacher acts as a facilitator during learning. If these features or characteristics are used effectively in a unit of integrated instruction, it will enhance the learners' acquisition of critical thinking skills and improve students' academic achievement

The major elements to be considered in designing an effective integrated instructional model should centre on a student-centred learning task, hands-on and practical activities (Treacy & O'Donoghue, 2014). They further emphasized that each learning task should be based on a productive task (inquiry, hands-on and group discussion) that relates to real life. In agreement with this other literature opined that when designing integrated instruction, there is the need for the instructional content to be contextualized and be characterized by features such as; inquiry, group work, hands-on activities and interaction among learners and the facilitator (Frykholm & Glasson 2005; Furner & Kumar, 2007; Treacy & O'Donoghue, 2014).

Similarly, Sampurno et al. (2015) adopted the definition of STEM education by Becker and Park (2011) to integrate STEM and disaster education (STEM-D). They highlighted six (6) features for the instructional process of STEM-D, the features are; 1) observation 2) identifying 3) discussion 4) question and answer 5) elaboration and 6) reflection. These features of STEM-D make it an innovative instructional approach that will increase the students' disaster literacy and enhance their STEM skills (Sampurno et al., 2015). While Furner and Kumar (2007) reported that in integrated instruction, an alternative form of evaluation should be employed such as achievement of the task, interviews, observation, self-assessment of students as well as standardised testing. Likewise, Crippen and Archambault (2012) in their study "scaffolding inquiry-based instruction with technology: a signature pedagogy for STEM education" reported that the essential features on how to best engage students' in STEM learning content. The features include; questions based on the real world, investigate to gather relevant data to answer the question or solve the problem, data analysis, collaborative discussions and evaluates findings concerning accepted standards as well as communicate their findings.

In a similar way, it was reported that designed-based science and real-world problem-solving are similar to the integration of the engineering design process in science learning (Fortus et al., 2005). The feature that was employed to design the instructional process was; a) contextualising the problem (defining the problem), b) Investigating the problem; c) group discussion; d) development of 3d models and e) evaluation. The data was evaluated quantitatively, and the findings revealed an increase in the test scores from pre-test to post-test and a strong correlation was revealed between the post-test score and the transfer of task than with the pre-test (Fortus et al., 2005).

Stohlmann et al. (2012) emphasised that a good way to make learning relevant and pleasurable is through integrated STEM education because it helps students acquire critical thinking and innovative skills (Morrison, 2006; Stohlmann et al., 2012). They argued that the effective practices and features for integrating science and mathematics provide insight into effective integrated STEM education approach. Zemelman, Daniels, and Hyde (2005) in Stohlmann et al. (2012) highlighted important features for mathematics and science instruction which includes; Hands-on activities, use of Manipulatives; Cooperative learning; Inquiry and discussion; Questioning and assumptions; Justifying ideas; reflection and solving problem and Integrate technology; The teacher acts as facilitator. Most of these features naturally support integrated STEM approach to teaching and learning.

It was observed that Stohlmann et al. (2012) adopted some elements to develop a STEM model on consideration for STEM instruction in middle school. He provided valuable data on how learning can be useful in the science classroom and enhance the transfer of knowledge and skills beyond the classroom. Treacy and O'Donoghue (2014) highlighted that the main elements to be considered in designing an effective integrated instructional model should centre on a student-centred learning task, hands-on and practical activities. Given the proceeding, some of the common features of STEM-based instruction are student-centred activities; hands-on activities, collaboration, inquiry and real-world problem. These elements or features will assist the learner to be actively engaged in the learning process and this corroborated the views of the constructivist.

Other researchers reported that STEM-based instruction is made up of six essential components which include; 1 authentic task; 2 engineering design challenges; 3 application of science and/or mathematics; 4 real-world open-ended problem; 5 student-centred approaches and, 6 emphases on teamwork and communication (Bybee, 2010; Guzey, Ring-Whalen, Harwell, & Peralta, 2017b; Moore, Johnson, & Peters-Burton, 2015; Stohlmann et al., 2012; Walker, Moore, Guzey, & Sorge, 2018). These essential components were taken into consideration in designing integrated STEM approach for this study.

### 2.4.2 Integrated STEM-based Instructional Methods

Literature has reported that STEM teaching and learning can be implemented using several methods such as problem-based learning (Basuki, Besari, Agata, & Hasyim, 2018; Lou, Shih, Ray Diez, & Tseng, 2011), project-based learning (Capraro & Slough, 2013; Crotty et al., 2017; Kasim & Ahmad, 2018). Problem-based learning and project-based learning involve elements of solving complex or open-ended problem. However, the two approaches are different. The difference between the two approaches is that problem-based learning focuses on building new knowledge by relating the open-ended, real-world problem to their prior knowledge and come up with new understanding and solution to the problem (Kasim & Ahmad, 2018). Project-based learning, on the other hand, involves students engaging in exploration and generation of ideas to solve a problem which involves building a product which could be an artefact or a process (Banks & Barlex, 2014). It can also be implemented using 5E; Engage, Explore, Explain, Elaborate And Evaluate (5E) model (Dass, 2015; Hiong & Kamisah, 2015; Kasim & Ahmad, 2018). It is reported that the 5E learning cycle aligns with the engineering design process and have been adopted as a model for the STEM-based instruction (Capraro, Capraro, & Morgan, 2013; Kasim & Ahmad, 2018); inquiry approach (Nadelson et al., 2013; Osman, Hiong, & Vebrianto, 2013; Toma & Greca, 2018) and Engineering Design Process (Guzey et al., 2016; Shahali et al., 2017; Wells, 2016).

It was observed that even though engineering breaks down boundaries between the disciplines of science, mathematics and technology education, it does not have a place in the secondary school curriculum (Daugherty, 2010). Therefore, using engineering design to integrate STEM disciplines will provide an important platform for students to acquire STEM skills and interest in engineering. This was supported by Moore et al. (2015) who sees integrated STEM as an approach to instruction which involves the content knowledge and practices of mathematics and science through the integration of engineering design process and appropriate use of technology. Students engagement in the engineering design process could enhance their critical thinking skills.

## 2.5 STEM Education and Critical Thinking

Critical thinking is an important goal of science education. However, for students to acquire this skill would require learning environment and instructional strategies that would help the learner to develop the ability to define a problem, generate and analyse information to solve a problem (Erkens et al., 2019; Kek & Huijser, 2011; Mathis, Siverling, Moore, Douglas, & Guzey, 2018). Integrated STEM classroom activities that foster experiences that are interdisciplinary and characterised by small group interaction, inquiry, and the open-ended problem can significantly impact students' ability to think critically (Asghar, Ellington, Rice, Johnson, & Prime, 2012; DeJarnette 2012; Duran & Sendag, 2012; Johns, 2012).

A study was conducted on an IT/STEM project investigation of critical thinking skills among urban and rural high school students (Duran & Sendag, 2012). A quasi-experimental design was adopted, and the instrument for data collection was pre-test and post-test critical thinking test. The project was characterised by independent and small group interaction. The result revealed that urban students' critical thinking abilities were significantly improved notably in the sub-skill of deduction and inference.

Students' critical thinking through justification and evidence claims using online simulation; space science and computational models was investigated. The study focused on the integration of science, mathematics and technology. Data collection was done using pre-post explanation scoring rubrics. The findings indicated that the explanation and justification of claims enhanced students' ability to think critically. It was concluded that science, mathematics and technology integration would enhance students' cultivation of critical thinking skills (Pallant, Pryputniewicz, & Lee, 2012).

Researchers have adopted several teaching and learning strategies to enhance students' ability to think critically; problem-based learning, designed based learning, social interaction, hands-on, minds-on and inquiry approaches (Carvalho et al., 2015; Duran & Sendag, 2012; Galloway & Anderson, 2014; Kek & Huijser, 2011; Treacy & O'Donoghue, 2014; Wells, 2016).

Given the preceding, integrated STEM approach (iSTEMa) in this study is characterised by collaboration, hands-on and minds-on activities, open-ended problems, questioning, and scientific investigation. Therefore, it is hoped that this approach could enhance students' critical thinking skills and achievement in genetics.

### 2.6 STEM-based Instruction and Students' Achievement

The quest to improve students' learning and achievement in the classroom has led to the adoption of several STEM models and strategies by scholars (Han et al., 2014; Tomkin, Beilstein, Morphew, & Herman, 2019; Yıldırım & Sidekli, 2017). The findings are mixed. Therefore, more research is needed. It is reported that instructional strategies that boost students' engagement and exploration during the learning process promote positive learning outcomes (Karbalaei, 2012).

The influence of designed-based STEM course on students' content knowledge, STEM conceptions and engineering views. The approach was characterised by the real-world problem, problem-based learning and designing a solution (product or process). The intervention lasted for 12 weeks, and the findings show that students understanding of science content was deepened (Aydin-Gunbatar, Tarkin-Celikkiran, Kutucu, & Ekiz-Kiran, 2018).

The effects of designed-based STEM curricular on students' achievement in science, engineering and mathematics was investigated. Quasi-experimental design was adopted, the findings show that the treatment group significantly improve their science achievement (Guzey, Harwell, Moreno, Peralta, & Moore, 2017a). Some other researchers use a STEM project-based and Problem-based approach which was characterised by the building of an artefact and problem-solving respectively. Students' achievement in science and mathematics was evaluated. The finding revealed that there was a significant difference between the achievement of the treatment and control group. It was concluded that integrating STEM through the project and Problem-based learning has the potentials to influence students' academic achievement in science and mathematics (English, Hudson, & Dawes, 2013; Fortus et al., 2005; Thomas, 2013; Zhbanova, Rule, Montgomery, & Nielsen, 2010).

The engineering design process has also been adopted as a context-based approach to instruction in the secondary school level, and the results revealed that the engineering-based group performs better in the science content test than the traditional group (English & King, 2015; Fantz & Grant, 2013; Wendell & Rogers, 2013). Cox et al. (2016) investigated how students could gain a deeper understanding of scientific concepts using the engineering design process. Their findings revealed that students who learn through engineering design project gained more knowledge of science concepts than the comparable group.

Similarly, a study was conducted that compares the performance of students in a standardised test between students who participated in a STEM intervention programme for starters and the control group (non-STEM intervention group) (Robinson et al., 2014). The findings of the research revealed that science process skills and science content knowledge of the intervention group were significantly higher than the control group. Similarly, (Guzey et al., 2017a) who conducted a case study on life science learning using engineering in K-12, a pre and post-test design was adopted. The findings showed higher gains in science and engineering concepts.

On the contrary, other researchers investigated the effects of STEM education on students' achievements in science, and the findings were found to be negative. For instance, James (2014) conducted a study to investigate the extent of STEM education influence on mathematics and science achievement among seventh-grade students. The study adopted a quantitative comparative method; the sample size was 631; the experimental group were 281 while the control group were 350. The data were analysed using the t-test. The result showed that the traditional mathematics and science group (control) perform significantly better than the treatment group. It was concluded that the STEM model of instruction in that given population was not associated with higher science and mathematics achievement (James, 2014)

Other researchers investigated the integration of mathematics, science, and technology through project-based learning, the major features of the instructional material are hands-on activities, small group interaction, and authentic assessment (Satchwell & Loepp, 2002). They concluded that integrated instruction did not influence the students' interest and motivation in science and mathematics, consequently, this could have negative effects on their mathematics and science achievement. The existing literature on STEM integrated instruction and students' achievement in science as reported above is inconclusive.

Most of the studies reviewed focused on students' achievement while this study focused both on students' critical thinking skills and achievement. None of these studies was conducted in sub-Saharan Africa and Nigeria to be precise, hence the need for this present research study

## 2.7 Instructional Design Models and iSTEMa

The preparation of iSTEMa is based on the constructivist learning theory as explained in the theoretical framework because the emphasis of the theory is on the development of higher order thinking skills (HOTS). Unlike the behaviourist theory, where the emphasis is on the development of lower thinking skills. In support of this assertion, Saat (2003) argue that instruction targeted at lower-order thinking skills (LOTS) acquisition should not employ the constructivist approach because this approach engages higher order cognitive processes.

An Instructional model is a systematic method of implementing the instructional design process for a specific educational approach or initiative (Morrison, Ross, & Kemp, 2004), An instructional model provides the basis for implementing a learning theory because it helps the designer to translate learning theory into an instructional material with components such as; activities, learning resources and evaluation methods (Smith & Regan, 1999). Dick, Carey, and Carey (2001) instructional model is considered as one of the most important and popular because it adopts the conventional elements of analysis, design, development, implementation, and evaluation (ADDIE). In this model the five significant elements are further subdivided into nine steps; a) needs assessment to establish the goals of instruction b) analysis of instruction, the learner and learning context c) establish achievement objectives d) assessment instrument e) instructional strategies f) instructional materials g) conduct formative evaluation h) revision of instruction i) conduct summative evaluation. These steps are linear, each of these elements is dependent the other (Dick et al., 2001)

However, Kemp Model to instructional design focuses on curriculum planning which is based on the learners' perspectives and not based on the learning content. The features that influence learning are considered as part of the features of Kemp model which includes; 1) need analysis and goals 2) instructional strategies 3) media choice 4) learning objectives 5) topics arrange in logical manner 6) teaching and learning activities 7) planning and development of instruction 8) evaluation 9) resources for instruction (Morrison et al., 2004). These elements of the Kemp model are arranged circularly.

The models may differ from each other with regards to the number and layout of the features as it relates to one another, however, each of the models emphasises on 1) need analysis 2) design 3) development and 4) implementation and 5) evaluation (ADDIE). ADDIE is a widely used approach for the development of training manual and instructional materials. It helps educators to clearly define a procedure to an instruction (Peterson, 2003). The ADDIE model is student-centred, and the phases are interconnected as well as iterative (Dick et al., 2001), and each phase of ADDIE is tailored towards the learning outcome. The phases of ADDIE are highlighted in the figure below;

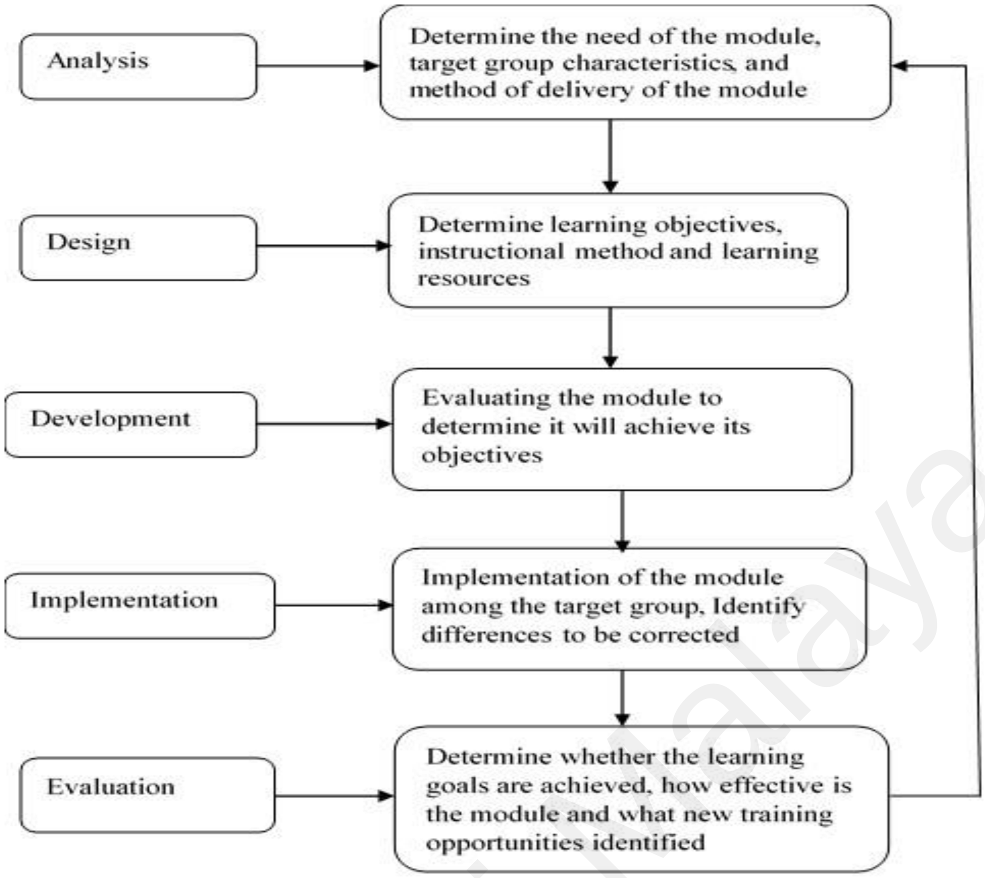


*Figure 2.1: A Graphical Illustration of ADDIE Process*

The ADDIE was adopted to design the integrated STEM instructional material (iSTEMim) for this study because it provides a consistent process to follow and it is widely used for the development of instructional materials. The iterative nature of ADDIE provides the opportunity to always improve previous phases (Mayfield, 2011)

## 2.8 Critical Thinking Skills

The ability to thinking critically is an inherently human endeavour. Hence, scholars have highlighted the need for schools to help learners acquire critical thinking skills at all educational levels (Kivunja, 2014; Zhou et al., 2013). It is vital because it is one of the skills that are important for dealing with global challenges (Kim & Choi, 2016). However, it is a complex phenomenon, and that can be seen in its varied definition and classification by experts. It is seen as the ability to analyse, evaluate and synthesised information to make a valid decision (Germaine, Richards, Koeller, & Schubert-Irastorza, 2016). Critical thinking is "the process of judgement that is self- regulated, giving reasoned consideration of the evidence, context, conceptualisation, methods, and criteria"(Facione, 1990).

Similarly, Ennis (1984) reported that critical thinking is "reflective and reasonable thinking that is focused on deciding what to believe or do" Ennis categorise critical thinking into four subskills; inductive reasoning, deductive reasoning, value judgement and identification of assumptions. Lipman (1988) sees critical thinking as a more complex ordinary thinking, critical thinking according to him involve careful argumentation, making logical conclusion base on set rules, providing opinions to substantiate proof and moving away from believing and assumption to hypothesising. More than two decades ago that Peter Facione and other researchers through a Delphi method established the definition of critical thinking as "purposeful, self-regulatory judgment which results in the interpretation, analysis, evaluation and inference as well as the explanation of the evidential, conceptual, methodological, contextual considerations upon which judgment is based" (Facione, 2006). From the above definitions of critical thinking, therefore, is skills at the higher levels of Bloom's taxonomical classification of learning objectives; analysis, evaluation and creating in the case of the revised Bloom's taxonomy of learning classification.

In Nigeria, the national policy on education stated that "the country's educational goals shall be set out concerning their relevance to the needs to the needs of the individual and those of the society, in consonance with the realities of our environment and the modern world." In view of the above, the realities of the modern world require citizens that can think critically to drive the economy of the 21$^{st}$ century (Pickering, 2010; Wagner, 2008). Students in Nigeria demonstrate a low level of critical thinking skills (Salami, 2013). Why are learners not demonstrating critical thinking skills? An intensive search for the reasons revealed the following; the teacher dominates classroom interaction, and knowledge acquisition during instruction is at lower thinking skills of Bloom's taxonomy characterize by memorization (Gimba, Hassan, Yaki, & Chado, 2018; Omilani, Akinyele, Durowoju, & Obideyi, 2018; Oyelekan, Igbokwe, & Olorundare, 2017; Pitan & Adedeji, 2012). Innovative instructional strategies that are student-centred and characterise by active learning that will stimulate thinking skills are not adopted, and evaluation focuses on facts and lower cognitive skills (Omilani et al., 2018; Oyelekan et al., 2017).

Given the preceding, to enhance learners' critical thinking skills, There must be a change in the way teachers teach, and students learn. Thus the integrated STEM approach leverage upon to enhance students' ability to think critically.

### 2.8.1 Teaching Critical Thinking Skills

The theory that supports critical thinking is rooted in Benjamin Bloom's work (Bloom, 1956) who classified the cognitive domain into six levels, each of the levels corresponds to the cognitive ability of an individual (Duron, Limback, & Waugh, 2006). Knowledge is a cognitive level focus on recall and memorisation. Comprehension deals with activities that lead to relating and organising information that is learnt. Application deals with applying knowledge according to the rules in a given situation. While analysis, synthesis and evaluation are critical thinking activities (Bloom, 1956; Duron et al., 2006). Teaching critical thinking effectively, teachers must target activities and experiences at a higher level of Bloom's taxonomy.

A meta-analysis on instructional strategies and critical thinking skills acquisition among learners (Abrami et al., 2015). He discovered that the results were mixed; however, some instructional strategies were more effective than others at improving critical thinking. Partnership for 21st-century skills (2007) suggested five major parts of the instruction be included to assist learners in developing critical thinking skills; ensuring learning content is relevant to student life, infusing critical thinking to all learning activities. Others include; creating opportunities for students to collaborate among peers and with the teacher. Ensure that students are actively engaged in learning by connecting instructions to real life experiences. There is a consensus that traditional classroom practices do not foster the development of critical thinking skills (Duron et al., 2006; Hatcher & Spencer, 2005; McDonald, 2012). However, there is no agreement on the best instructional strategy that could be used to foster students' ability to think critically. Consequently, how to teach critical skills is a fundamental issue for teachers and researchers.

#### a Subject Specific Critical Thinking Instruction

There seem to be two schools of thoughts on critical thinking instruction in literature. One school of thought believe that critical thinking skills should be taught as a skill in a given subject or specific discipline (Facione, 2007; Tiruneh et al., 2017). Critical thinking ability is dependent on the content knowledge of the individual subject and linked with a deeper understanding of subject-specific content (Tiruneh et al., 2017). Hence, the ability to think could be enhanced through the explicit integration of critical thinking in specific subject instruction (Moore, 2011). For instance, McPeck (1981) agrees with the assertion of teaching critical thinking within a given subject. He maintains that teachers should teach critical thinking in a psychology class different from biology class. Several studies have implemented subject specific critical thinking skills research (Abrami et al., 2015; Chan, 2013; Tayyeb, 2013). Recent literature has reported improved critical thinking skills among secondary school students globally in domain-specific evaluation (Nuswowati & Purwanti, 2018; Saputri et al., 2019; Tiruneh et al., 2017). The domain-specific instruction of critical thinking is also called explicit critical thinking integration.

### b General Critical Thinking Instruction

Contrary to the subject-specific, the second school of thoughts believed that critical thinking skill could best be instructed as a general skill that can be applied to all disciplines (Facione, 2006; Siegel, 1988). The opponents of subject-specific instruction of critical thinking believe that critical thinking is a set of skills that can be applied across domains such as science, history and everyday life (Davies, 2013; Halpern 1998). Similarly, it was observed that instructional content differs from one subject to another, but there are common grounds of thinking practices across domains (Ennis, 1991; Halpern, 2014). Therefore, opponents of subject-specific learning of critical thinking insist that critical thinking should be taught as a general skill and not in a subject-specific context.

Early efforts by previous researchers were to assist students in acquiring critical thinking skills in a learning context where general critical thinking is taught independently of the subject matter (Abrami et al., 2015). However, the focus recently has shifted towards entrenching critical thinking embedded in subject matter, with the hope it will enhance the development of critical thinking skills in subject domain and facilitate the transfer these skills to problem-solving in everyday life (Halpern, 2014; Lawson, 2004; Li & Payne, 2016; Tiruneh, Verburgh, & Elen, 2014). Given the proceeding, this study adopted an explicit integration of critical thinking.

Previous literature has highlighted that teaching, and learning approaches characterised by active learning through mental processes such as; justification, evaluation, analysis and explanation enhance learners' critical thinking skills (Chatila & Husseiny, 2017; Kim, Sharma, Land, & Furlong, 2013; Lay & Osman, 2017; Pallant et al., 2012). For instance, Kim et al. (2013) examined the impacts of active learning strategy on undergraduate critical thinking skills. The approach was characterised by authentic task, collaboration, scaffolding and individual reports. The findings indicated that students' critical thinking skills were improved. Kraus, Sears, and Burke (2013) considered the impacts of the teaching module characterised with group discussion and debate on students' critical thinking. The conclusion showed that the teaching module enhanced students' critical thinking skills.

Therefore, the integrated STEM approach is not only exploratory but is characterised by a real-life problem, driving questions, brainstorming and mental processes which may enhance critical thinking skills. It, therefore, seems to have the potentials to reduce or close the gap between what is learned and the expected in the real world.

### 2.8.2 Critical Thinking Subskills

Critical thinking skills will assist students in adapting to the evolving world (Atabaki et al., 2015; Paul, 2004; Zhou et al., 2013). However, critical thinking is complex, and that can be seen in its varied definitions and have been classified by researchers in several sub-skills with a consensus that critical thinking can be taught.

Facione (1990) classified critical thinking into the ability to; analyse, infer, interpret, explain and self-regulation. Critical thinking is seen as "reasonable reflective thinking focused on deciding what to believe or do" It was reported that critical thinking is an essential factor of the problem-solving process (Ennis, 1991).

Watson and Glaser (1991) reported that critical thinking is a composite of knowledge, attitudes and skills and is classified into; inference, recognising assumption, deduction, interpretation and evaluating arguments. These subskills can be measured using the Watson Glaser Critical Thinking Appraisal (WGCTA) instrument (Watson & Glaser, 1991)

Ennis (1984) classified critical thinking subskills into; Deduction, Induction Credibility, value judgement, observation, defining and assumption Identification. Lipman (1988) reported that critical thinking is complex compared to reasonable thinking. He classified critical thinking into; argumentation from facts, a conclusion based on criteria, evidence-based opinion, formulation of hypothesis and assumption.

Halpern (1998) Critical thinking subskills were also classified into; analysis, inference, hypotheses, problem-solving, decision making and using probability rather than uncertainty. Sternberg (1984) classified critical thinking into problem identification and solving problem, conclusion, evaluating and monitoring the problem-solving process, information processing which involves evaluating, analysing, classifying, comparing and categorising.

Given the above review on critical thinking sub-skills or components, it was observed that there is a limited consensus among researchers and educators on critical thinking subskills. However, there are similarities among researchers in naming the sub-skills. This research study adopted the Watson and Glaser classification of critical thinking sub-skills because it is the most established and widely used across nations (Karbalaei, 2012; Yildirim & Özkahraman, 2011). Furthermore, most of the subskills of Watson Glaser appear in other authors classification as indicated in Table 2.1

*Table 2.1*

*Classification of Critical thinking Skills*

| S/No | Author and year | Student Level | Subskill |
|---|---|---|---|
| 1 | Cornell Critical Thinking Test | 5-12 | Induction, deduction, credibility, identification of assumption |
| 2 | Facione (1998) | 9-12 | Analysis, evaluation, inference, deduction, induction and overall reasoning |
| 3 | Halpern (1997) | | Verbal reasoning, arguments, analysis, formulating hypothesis, decision making and problem-solving |
| 4 | Watson and Glaser critical (1980) | 10 and above | Inference, recognition of assumption, deduction, interpretation and evaluation |



The subskills adopted based on Watson Glaser classification includes; inference, recognition of assumption, deduction, interpretation and evaluation includes:

a **Inference.**

This is one's ability to make decisions or draw early conclusions from observed facts from a given statement, opinion or problem (Watson & Glaser, 2008). The ability to infer involves the use of available evidence to make an early judgement; this type of thinking is based on the need to solve an ill-defined problem (Ruggiero, 2012). Similarly, Black (2012) accentuates that inference is the ability to determine the implication of a view, claim, and hypothesis to draw an early conclusion. On the other hand, the inference is also seen as making a valued judgement (Yildirim & Özkahraman, 2011). Duran and Dökme (2016) investigated an inquiry-based instructional approach to 6$^{th}$-grade critical thinking skills. The approach was characterised by authentic task, question prompts, and collaboration, the employ quantitative design (pre-test and post-test control group experimental) design. The finding shows that the experimental group perform. Therefore, the skill of inference could be enhanced when an individual views the problem from several perspectives before drawing an implication. Therefore, students' ability to infer was considered based on their ability to draw an early conclusion based on available facts about genetic laws, concepts, and principles. During engaging the problem, for example, students analysed the problem into its components facts and based on the facts make inference on the possible cause of the problem. Given the proceeding, inference score in this work is seen as the ability to discover facts, query evidence to draw rational conclusions. Consequently, Dwyer, Hogan, and Stewart (2014) reported that the ability to infer is an exclusive form of synthesis where conclusions are drawn based on evidence or facts

b **Recognition of Assumption**

A critical thinker should have the ability to analyse and recognise assumption or arguments. Wade (1995) accentuates that an important way to enhance students' skill of recognising assumption is to ask them to highlight the components that underline information or conclusion. Facione (2011) opined that the critical thinking skills would be enhanced when the problem presented to students are ill-defined that will promote the disposition for complex thinking. Instructional practices that will promote learners critical thinking skills such as recognition of assumption among others provides the opportunity for a more deeper understanding of preposition or information and enhance decision making and real-life problem-solving (Dwyer et al., 2014). This is consistent with an integrated STEM approach. Thus, it is an individual ability to recognise propose an assumption based on a statement. The assumption is something presumed or taken for granted, for example, when one says he will be a pharmacist in December, it is assumed that one will be alive in December and that the school will judge one to be eligible to be a pharmacist. Recognising assumptions assist individuals in realising gaps in statement or information and correctly judging their validity (Elson, Hartman, Beatty, Trippe, & Buckley, 2018).

c **Deduction**

It is the logical breakdown of a given component, statement or problem into its parts and conclusion are drawn. Deductive subskill of critical thinking is the ability to reason from general to specific perspective or reason from a global truth to a specific situation (Facione, 2011). Kurfiss (1988) reported that critical thinking skills are enhanced when individuals are involved in investigating complex problem or phenomenon to reach a logical, justifiable conclusion. Dealing with complex problem assist learners engage the mental skill of deduction among others to understand the complex problem. Engaging students exploration of a problem through phases or stages that will assist learners in completing or solving a real-life problem or authentic task assist them in developing deductive skills (Heit & Rotello, 2010). Given this, learners learning style is greatly influenced by the instructional approach which has an impact on students' deductive skills. Therefore, students' deductive ability is observed when the logical conclusion is consistent with available information. Cheng, She, and Huang (2018) observed that deduction is a thinking skill that provides students with the opportunity to follow the specific cognitive operation. This is consistent with an integrated STEM approach to learning and similar to the way professional work in real-life through a sequence to arrive at a logical conclusion.

d Interpretation

This is a mental process that seeks to clarify meaning, categorise information and decipher significance; it involves the ability to interpret problem and information (Watson & Glaser, 2008). Instructional approaches characterised by problem-solving provides the latitudes to apply science concepts and principles to construct a rational explanation about the problem and create a viable solution, in the process new knowledge is acquired. Questioning is an important cognitive strategy that promotes cognitive reasoning like interpretation, in a learning environment that is student-centred, teachers should engage students in meaningful learning by asking questions that require interpretation among others instead of providing explanation and interpretation (Hmelo-silver & Barrow, 2008). Colletti (2011) conducted a study on the effects of completing an authentic task on critical thinking skills development; the authentic task was characterised by analysis of a project, collection of information, collaboration, interpretation and creating a final product. The finding shows that there was no significant difference between the treatment group and the control group in the subskill of interpretation. The reason was attributed to lack of sufficient time to practice the skills of interpretation and analysis. In this study, interpretation could be observed during group discussion as students interpret and defend their ideas

e Evaluation of Arguments

The ability to think critically involves an individual's skill to define a problem, select important information to solve a problem, apply or integrate knowledge in a new environment, perform evaluation and draw a conclusion (Watson & Glaser, 2008). These are consistent with integrated STEM approach. The NGSS Lead States (2013) document highlighted the need to assist students in acquiring skills of planning, investigating, interpreting data and evaluation. Therefore, an important strategy to promote the ability to evaluate is to engage students in solving the real-life problem instead of routine problem exercise from the textbooks (Carvalho et al., 2015). Learning activities characterise by the real-life problem is reported to bridge the gap between the classroom and the real-life (Weber, 2014). Similarly, Colletti (2011) found an improvement in the ability to evaluate among students who engage in authentic task compare to the traditional group. Given the preceding, iSTEMa could enhance evaluative skills because the approach is characterised by the real-life problem, driven by questioning, generation of data and the application of scientific principles and concept to design solution as well as assess their final solution

### 2.8.3 Development of Instrument for Assessing Critical Thinking Skills

Critical thinking skills proficiency is one of the parameters to measure success in education so that an individual can make a better decision and become a citizen that is well informed (Abrami et al., 2015; Halpern, 2014). That is probably why critical thinking is widely considered as one of the most important goals of science education (Li & Payne, 2016; Mapeala & Siew, 2015; Tiruneh et al., 2017)

Most well-known critical thinking tests are connected to general problem-solving. Therefore, there are limited established test instruments for critical thinking in subject-specific especially the science domain. Hence, the need to prepare and validate a critical thinking test that is science content specific. The lack of consensus on the meaning of critical thinking and the core skills of critical thinking has led to the categorisation of several critical thinking sub-skills and thus, making critical thinking assessment a crucial issue (Atabaki et al., 2015; Lin, 2014; Tiruneh et al., 2017).

Several researchers have developed several tests to assess critical thinking skills. The test instruments were categorised into several categories (Abrami et al., 2015). Which include the following instruments:

*Standardised Test Instruments;* these are multiple choice critical thinking test which is standardised in nature example include; Watson-Glaser Critical Thinking Appraisal, Cornel Critical Thinking Test, California Thinking Disposition Inventory (Ennis & Millman, 1985; Facione, 1990; Facione, Facione, & Giancarlo, 1996; Watson & Glaser, 1980)

*Test Developed or prepared by teachers;* these are critical thinking assessment instrument developed by the teacher by collecting students' response through open-ended questions, essay test and interview questions (Abrami et al., 2015). An example is a test developed to critical thinking skills in physics, specifically in the content of electricity and magnetism (Tiruneh et al., 2017)

*Test prepared or developed by researchers;* these are instrument prepared by researchers who are serving as teachers to assess students' achievement in thinking skills, and during the study, the researcher will serve as an instructor (Abrami et al., 2015; Jungwirth & Dreyfus, 1990). Example of this is the critical thinking application test to assess reasoning skills (Zohar & Tamir, 1993)

*The test developed by Researchers or study Authors;* this is a test instrument that is prepared or developed by study author for use in a specific study and is non-standardized. Example, critical thinking test, developed to measure critical thinking skills by (VanTassel-Baska, Zuo, Avery, & Little, 2002)

*Secondary-sources Methods;* these are test instruments that are adapted or adopted from other sources, with or without modification to fit a particular research situation or requirements. Example of critical thinking test develops to measure critical thinking skills in science-related content (Alrubai, 2014; Tiruneh et al., 2017).

Given the preceding, the secondary source method and test prepared by researchers are adopted for this study. This will allow the researcher to adopt and adapt critical thinking test questions from secondary sources and formulate some items based on the definition of the sub-skill. In this study, the fundamental step of critical thinking test preparation was to ascertain the critical thinking components or subskills. Therefore, the researcher adopted the components or subskills that are common across several general critical thinking tests such as;

Watson-Glaser Critical Thinking Appraisal (WGCTA (Watson & Glaser, 1980);

Cornel Critical Thinking Test (CCTT) (Ennis & Millman, 1985);

California Thinking Disposition Inventory (CCTST) (Facione, 1990);

Halpern Critical Thinking Assessment (HCTA) (Halpern, 2010); and

Ennis-Weir Critical Thinking Essay Test (EWCTET) (Ennis & Wier, 1985).

The standardised test instruments are more reliable because of their established reliability and validity and could be enhanced. A summary of standardised test instruments is given in Table 2.2

Table 2.2

*Critical Thinking Test Instrument, Components and Test formats*

| Critical Thinking Instrument | Critical Thinking Components | Test Format |
|---|---|---|
| WGCTA | Inference, Recognition of assumption, Deduction, Interpretation and Evaluation of Arguments | Multiple Choice |
| CCTT | Induction, Deduction, Credibility, Prediction and valued judgement, Fallacies and assumption Identification. | Multiple Choice |
| CCTS | Analysis, Evaluation, Inference, Deduction, Induction and Overall Reasoning Skills. | Multiple Choice |
| HCTA | Verbal Reasoning, Arguments Analysis, Hypothesis Testing, Likelihood Analysis, problem-solving and Decision Making. | Multiple Choice and Constructed Response |

In this study, Watson-Glaser Critical Thinking Appraisal (WGCTA) components or sub-skills and their definitions are adopted because all the sub-skills WGCTA appear in other multiple-choice tests as highlighted in Table 2.4. Most importantly, the subskills of Watson and Glaser critical thinking instruments measures an individual's ability to define a problem, to choose important information for a solution to a problem, recognise whether an assumption is made or not, to formulate hypotheses, to perform evaluation and draw a conclusion. These skills could be related to solving a design-based problem where the students will define the problem, generate ideas, evaluates the ideas and select the best idea to solve the problem.

Consequently, there is an overlap between sub-skills of WGCT components and the phases iSTEMa in this study, for example, WGCTA measures an individual ability to define the problem, formulating hypotheses and select important ideas for a solution to a problem which is similar to the activities in phase 1 and 2. The instrument also measures evaluation of argument and deduction which is also similar to the evaluation phase and communication phase of iSTEMa. Therefore, the set of science and engineering practices are closely related to the sub-skill of critical thinking. The WGCTA is designed for grade nine (9) or above (Watson & Glaser, 1980) while this study focused on eleventh-grade. Therefore, the researchers think its structure and definition of critical thinking skills by Watson and Glaser were more appropriate for this study. Woehlke (1985) on the other hand argued that the WGCTA reading level was for grade 9, but the cognitive skills were higher than grade ninth. These reasons prompted the researchers to adopt the instrument.

### 2.9 Empirical Finding on Critical Thinking Skills

The trend in science education instruction is fixated on enhancing students' development of scientific and critical thinking as well as experiences on how STEM professional work in real-world settings. Hence, a curricular approach focusing on integrating instructional content with thinking skills have been recommended by researchers because the traditional model of instruction does not enhance learners' ability to think critically (Avargil, Herscovitz, & Dori, 2012; Chukwuyenum, 2013; Kek & Huijser, 2011). To enhance critical thinking skills, the facilitator must focus on strategies and activities that engage learners higher-order cognitive abilities. In support of this, Loes, Salibury, and Pascarella (2015) researched on students' perception of effective instruction and the development of critical thinking skill. The finding revealed that students' perception of organised instruction is positively correlated with critical thinking gains.

Several instructional strategies have been implemented in the science classroom to influence critical thinking development among learners (Duran & Sendag, 2012; Zhou et al., 2013). For instance, literature has reported that instructional activities build on social interaction (collaborative, cooperative, peer tutoring and group discussion) have significantly improved students' thinking skills compare to traditional instructional approach (Mandusic & Blaskovic, 2015; Styron Jr, 2014). On the contrary, Shim and Walcza (2012) in their study the effects of faculty instructional practices on the acquisition of critical thinking skills, the results showed that class presentation and group discussion decreased the assessed critical thinking skills

Problem-based learning characterised by the open-ended problem, group discussion and generation of ideas has also been reported to significantly influence the development of critical thinking skills (Asyari, Al Muhdhar, Susilo, & Ibrohim, 2016; Batdı, 2014; Carvalho et al., 2015). On the contrary, Temel (2014) investigated the effects of Problem-based learning on critical thinking disposition and the perception of problem-solving abilities among pre-service teachers. The results showed no significant effects of Problem-based learning method on critical thinking disposition

Other instructional strategies have also yielded significant effects in assisting learners in developing critical thinking skills especially in science instruction; Task-based learning which is characterised by students' centred activities (Han & Brown, 2013; Zhou et al., 2013). Tsui (1999) conducted a study on the effects of the instructional technique on students' growth in critical thinking skills. The finding revealed a positive correlation between critical thinking and instructional practices such as conducting a research project, group projects and collaboration. On the contrary, the findings also revealed a negative correlation between critical thinking and the traditional lecture method using the multiple-choice question that centred on recall of facts. This implies that traditional instructional strategies are suited for enhancing critical thinking development among learners.

Given the above empirical based evidence, it is, therefore, clear that instructional approaches characterised by open-ended problem-solving, inquiry, design-based activities, collaboration and questioning which lead to active students' participation in the learning process will enhance the development of critical thinking skills. Consequently, it is hoped that iSTEMa will enhance the development of critical thinking among learners.

## 2.10 Higher Order Thinking and Critical Thinking Skills

Higher order and critical thinking skills have been highlighted as essential skills to be inculcated in learners, therefore, these skills have been highlighted in several curricular documents (Council of Ministers of Education, 1997; FitzPatrick & Schulz, 2015; National Research Council, 2012; Saido, Siraj, Nordin, & Al_Amedy, 2015). Higher Order thinking skills (HOTS) are regarded as the three top skills of Bloom's taxonomy of learning objectives; analysis, evaluation and synthesis (Bloom, 1956; Krathwohl, 2014).

HOTS was also described as the use of abstract thinking structures and the organisation of ideas, information and thoughts into a cohesive scheme to make a judgment (Barak & Dori, 2009). It is a non-algorithmic means of thinking that results in several solutions. Brady (2012) observed that HOTS is view as a unique ability; it is employed by everyone in our daily life to imagine, formulate hypotheses, make judgments, comparison and conclude. HOTS are usually activated when an individual is confronted with an unacquainted scenario, problem or a decision to make.

The skills of HOTS (analysis, evaluation, and synthesis) assist in enhancing the transfer of knowledge acquired to a new environment (Saido et al., 2015; Yahya, Toukal, & Osman, 2012). Some scholars see HOTS to include; critical thinking skills, reasoning, and evaluation; these skills are employed in problem-solving (Brookhart, 2010; Schulz & FitzPatrick, 2016). Critical thinking skill is considered a major component of HOTS as reported by (Saido et al., 2015; Zachariades, Christou, & Pitta-Pantazi, 2013).

While others use HOTS and critical thinking interchangeably (Ramos, Dolipas, & Villamor, 2013; Saido et al., 2015; Schulz & FitzPatrick, 2016; Shaughnessy, 2012), for example, Schulz and FitzPatrick (2016) in their study, the understanding of teachers on critical thinking and HOTS; what it means for their instructional practices. They used critical thinking and HOTS interchangeably. Ramos et al. (2013) reported that cognitive process such as analysis, inference, an evaluation could be seen as HOTS or critical thinking skills. Given this, the subskills or components of HOTS (analysis, evaluation, and synthesis) are also highlighted in critical thinking skill components. For example, Facione (1990) classified critical thinking components into; analysis, evaluation, inference, deduction, induction and overall reasoning. Watson and Glaser (1980) classified critical thinking components to inference, deduction, interpretation, evaluation and recognition of assumption. HOTS is linked to critical thinking skills because activities that could assist in enhancing learners critical thinking skills could also enhance HOTS (Barak & Dori, 2009; Schulz & FitzPatrick, 2016). For example, Barak and Dori (2009) carry out a study on enhancing HOTS among in-service science teachers using embedded assessment, the HOTS activities were characterised by using group discussion, debates and evaluation of science education related articles the findings show that participants critical thinking skills were also enhanced. Even though there is a link between HOTS and critical thinking skills, this study focuses on using iSTEMa to enhance secondary school students' critical thinking skills.

## 2.11 Critical Thinking Skills and Students' Achievement

The link between critical thinking and achievement is worth highlighting because they are important variables in this study. Literature on enhancing critical thinking in biology (Azizah & Putra, 2015; Lazarowitz & Naim, 2012) and science education (Evren, Bati, & Yilmaz, 2012; Forawi, 2016; Zhou et al., 2013) Critical thinking skills and students' achievement have been linked in Literature (Akyol et al., 2010; Coutinho, Wiemer-Hastings, Skowronski, & Britt, 2005; Ghanizadeh, 2016; Lazarowitz & Naim, 2012; Zohar & Peled, 2008)

There is a consensus among literature; firstly, there is the need to assist learners in developing critical thinking skills and improving their academic achievement in science subjects. Secondly, the development of critical thinking leads to improve academic achievement because instruction or learning becomes more meaningful when learners engage in activities that assist them in developing thinking skills (Coutinho et al., 2005; Forawi, 2016; Ghanizadeh, 2016). These activities includes Hands-on and minds-on activities (Galloway & Anderson, 2014; Monvises, Ruenwongsa, Panijpan, & Sriwattanarothai, 2011) collaboration (Chatila & Husseiny, 2017; Mandusic & Blaskovic, 2015) inquiry (Duran & Dökme, 2016), open-ended problem (English & King, 2015; Forawi, 2016) design based and problem-solving (English et al., 2013; Kek & Huijser, 2011) and questioning (Corley & Rauscher, 2013; Santos, 2016).

It was reported that critical thinking skills development among learners improves academic achievement because critical thinking task assists in deepens learners understanding (Karbalaei, 2012). Akyol et al. (2010) argue that higher order thinking task improves students' achievement in science. Students with skills of analysis, evaluation and inference are likely to have better academic performance in science, indicating that critical thinking skills may influence students' performance (Ramos et al., 2013). Therefore, critical thinking and student achievement in science complement each other if learners are engaged in higher order thinking task. In this study, it is hoped that an integrated STEM approach will engage learners' higher cognitive abilities leading to critical thinking development and improve their performance in genetics.

## 2.12 Students' learning Ability

Academic ability grouping is the classification of students according to their academic achievement. Ability grouping is also called rank group and ability class. The practice of students grouping based on their ability is one of the techniques to increase students' academic achievement by creating a conducive environment for learning (Aldan, Karademer & Ucak, 2009). There are two types of ability grouping in educational practice that is most commonly used; between class grouping and within a class grouping. Between class ability grouping is a school practice of grouping students of similar ability in the same class (homogeneous class) while, within class grouping refers to grouping students of similar ability within a single class, and this is mostly done by an individual teacher (Slavin, 1990 & Robinson, 2008).

The proponents of ability grouping believe that it allows teaching and learning to encourage high achievement and providing remedial treatment for low achievers (Slavin, 1990). They argue that in a mixed-ability grouping, classroom instruction may be to the detriment of one group, for example, if the instruction is at an average pace, it might be boring for high achievers and probably too fast for low achievers, thus creating an unconducive environment for the students to learn. Those who argue against ability grouping observed that when students are grouped according to their ability, the lower ability group will receive less quality instruction while the high ability group will receive high-quality instruction, and this will increase the gap in achievement between them. In this study, the researcher adopted heterogeneous or mixed ability grouping to establish each group performance in an integrated STEM environment.

As schools struggle to bring all students up to the minimum proficiency level, instruction must be tailored towards students' individual needs and adequate support must be put in place to ensure that the challenge is being met (McDonald Connor & Morrison, 2016). Acara, Tertemizb, and Taşdemirc (2018) determined the effect of STEM-based instruction on mathematics, and science achievement. The findings indicated that students improved in their science and mathematics scores. They recommended further research to determine the effects of STEM education based on students' academic abilities (high, and low).

Students' ability has been researched in the last decades, but the finding has so far been inconclusive (Amponsah, Kotoka, Beccles, & Dlamini, 2018; Karademİr & Uçak, 2009; Raes, Schellens, & De Wever, 2013; Slavin, 1990). It is reported that higher achieving students perform better in the problem-solving task than lower achieving student because lower achievers cannot cope with higher order thinking task that requires analysis, synthesis, and evaluation (Bybee, 2010; Change the Equation, 2012). Other researchers have reported achievement gains among high, medium, and low achievers when instructional strategies that are learner centred were used (Brulles, Saunders, & Cohn, 2010 & Rogers, 2007). Raes et al. (2013) In the study collaborative web-based inquiry to bridge the science education gap in secondary school. The result which that high ability students perform better than the medium and lower ability students in mathematics

On the contrary, Yu et al. (2010) in their findings reported that low achievers perform better compared to medium and high academic achievers in a non-traditional test, this implies that low achievers will do well in higher order thinking skill such as critical thinking skills. Depending on the instructional strategy or technique as well as the richness of the instructional process in terms of activities and resources, low and medium achievers can perform well compared to their high achievers' counterparts in a scientific task. For example, Gambari et al. (2013a) examine the effectiveness of video-based cooperative, competitive and individualised instructional strategy on high, medium and low academic achievers using video instructional package. The findings revealed that students' ability does not affect their achievement. Gambari (2010) also reported that ability grouping has no significant effects on learners' achievement in student-centred strategies. Therefore, instructional strategies that facilitate active learning, exploration which are student-centred may bridge the achievement gap between high, medium and low ability students

Because of the inconclusiveness of literature on the interaction of students' ability on their academic learning outcomes in science and mathematics. Ability grouping is considered as a moderating variable in this research study. To explore, whether the integrated STEM education approach will assist in reducing the achievement between high, and low achievers.

### 2.12.1 Ability Classification

Students grouping into high, medium and low achievers have been done severally by researchers; Zady, Portes, and Ochs (2003) adopted specific score to group high, medium and low achievers ($\leq 50$ lower achievers and high achievers is $\geq 70$), this suggests that $\geq 50$ - $\leq 69$. Cumulative percentile to assign students to the different ability group have also been suggested. Other researchers reported that ability groups can be classified based on the criteria of the test provider. Texas Education Agency (TEA) for example, classified her test into "did not met standard" ( > 31/50 or >60% as low achievers) "met standard" ( 31-44/50 or 62-88% medium achievers) and commended performance (≥ 45 or 90% and above high achievers) (Han , Capraro, & Capraro, 2015; Texas Education Agency, 2009). Given the preceding, using students' average prior science achievement in the previous year, this current study adopted ≥ 60% as high achievers, and ≤ 59 as low achievers.

## 2.13 Genetics Teaching and Learning

Genetics deals with heredity and variation. It is a branch of biology that explains the resemblances and differences among living organism of the same descent. Inherited genes from parents express their self in specific characters such as physical characteristics and genetic disorders (Tamarin, 2007). The fundamental role of genetics in the society especially in the area of human health and the environment makes the difficulty of teaching and learning genetics more disturbing (Jalmo & Suwand, 2018; Mills Shaw et al., 2008).

Research literature in more than two decades have revealed that genetics is one of the difficult concepts to teach and learn which has led dwindling achievement especially at the secondary schools (Allen & Moll, 1986; Atilla, 2012; Haambokoma, 2007; Lewis & Wood-Robinson, 2000; Mthethwa-Kunene et al., 2015; Stewart, 1982; Tsui & Treagust, 2010). For instance, Atilla (2012) investigated biology topics that are considered difficult by students, he adopted a mixed method research design, with data analysed both quantitatively and qualitatively, the instrument used for data collection was questionnaires and interview respectively. The results revealed that cell division, genes and chromosomes among others, are difficult concepts to learn in biology. The finding also revealed that the problems could be overcome by linking biology learning content to real life.

Several researchers have employed different instructional strategies in teaching and learning genetic especially at the secondary level of education (Agboghoroma & Oyovwi, 2015; Muraya & Kimamo, 2011). Some of the instructional strategies or approaches include; Web-based science inquiry (Williams , DeBarger, Montgomery, Zhou, & Tate, 2012; Williams, Montgomery, & Manokore, 2012); 5E Learning cycle (Dogru-Atay & Tekkaya, 2008); Annotated drawing (Danmole & Lameed, 2014; Dikmenli, 2010); cooperative and peer tutoring (Jibrin & Zayum, 2012; Muraya & Kimamo, 2011) concept mapping instructional strategy (Agboghoroma & Oyovwi, 2015). Tsui and Treagust (2010) evaluated students' scientific reasoning in genetics using multiple representation of genetic phenomena. Similarly, (Tsui & Treagust, 2007) analysed students' conceptual status in the understanding of genetics. Most of this literature is linked to students' academic achievement in genetics among secondary school students.

Other researchers explore three modes of instruction, students' "Hands On" which focus on the construction of a three-dimensional model of the cell and its organelles, the second mode is the teacher demonstration of three-dimensional model of the cell structure and the third model is using the conventional model to teach the cell structure (Lazarowitz & Naim, 2012). The result revealed that the three groups were comparable before treatment, but after treatment, there was a significant difference in the post-test results. The hand on group students who built a three-dimensional model of the cell structure had a significant academic achievement than the other two groups. From the finding, it was concluded that learners irrespective of ability to learn better when they actively participate in the learning process.

Given the above review of literature on genetic instruction, it is seen that researchers have explored instructional strategies on genetics and students' achievements. None of this literature reviewed explores thinking skills such as critical thinking. Also, none of those literature explores the effects of the integrated STEM approach on students' achievement in genetics. Thirdly, even though there are several types of research on teaching and learning of genetics, underachievement of students in genetics persist, especially at secondary school level (Daramola and Lameed, 2014). Limited literature has been identified that link genetic to higher order thinking skills. Hence, the need to explore the effect of integrated STEM approach on students' critical thinking skills.

## 2.14 Summary of Literature Review

Literature has shown that the STEM education is the instructional reforms that are trending globally, because of its potentials to prepare learners for meaningful and successful leaving in the $21^{st}$ first century (Bybee, 2010; Morrison, 2006). It is a paradigm shift from the teacher-focused instructional practices to the learner-centred instructional practices. However, there is no accepted operational definition of STEM education by experts (Blackley & Howell, 2015; Brown et al., 2011; Bybee, 2010).

Literature has highlighted that STEM teaching and learning can be implemented using several approaches such as problem-based learning (Lou et al., 2011), inquiry (Nadelson et al., 2013; Osman et al., 2013; Toma & Greca, 2018), project-based learning (Capraro & Slough, 2013; Crotty et al., 2017; Kasim & Ahmad, 2018) while others believe that integrated STEM can be implemented using the Engineering Design Process (Guzey et al., 2016; Shahali et al., 2017; Wells, 2016). There are six fundamental components of STEM-based instruction which includes; 1 authentic task 2 engineering design challenges 3 application of science and/or mathematics 4 real-world problem 5 students' centred 6 emphases on teamwork and communication (Bybee, 2010; Guzey et al., 2017b; Moore et al., 2015; Stohlmann et al., 2012; Walker et al., 2018). Research studies have documented the advantage of secondary school students participating in STEM education to include improved learning achievement and positive attitudes towards STEM (Capobianco, Yu, & French, 2014; English & King, 2015; Guzey et al., 2017b; Shahali et al., 2017; Wendell & Rogers, 2013). However, there is limited literature linking integrated STEM-based approaches to students' development of critical thinking. Literature indicated a clear gap to investigate the impact of integrated STEM approach.

Literature has revealed that critical thinking is an essential goal of education and needed for meaningful living in the 21st century (Facione, 2011; Germaine et al., 2016; Kivunja, 2015). It is enshrined as one of the goals of education in many countries. However, scholars have observed that students are deficient in critical thinking skills (Bensley & Spero, 2014; Stapleton, 2011). Critical thinking is complex and can be seen in its different definition and classification (Facione, 1990; Halpern, 2010; Watson & Glaser, 1991). Some scholars agreed that students' ability to think critically could be enhanced using effective instructional approaches (Drummond, 2012; Fahim & Masouleh, 2012; Marin & Halpern, 2011). It was also discovered from the literature that embedding critical thinking within specific subject instruction enhances students' ability to think critically (Behar-Horenstien & Niu, 2011; Marin & Halpern, 2011; Tiruneh et al., 2017). Students' ability to think critically can be assessed using standardised critical thinking test (Zimmerman & Land, 2014). Standardised critical thinking test or instrument includes; Watson-Glaser Critical Thinking Appraisal, Cornel Critical Thinking Test, California Thinking Disposition Inventory (Ennis & Millman, 1985; Facione, 1990; Facione et al., 1996; Watson & Glaser, 1980).

There seems to be a link between STEM instructional elements and critical thinking elements. Therefore, Integrated STEM classroom activities characterised by small group interaction, inquiry, generation of ideas, and Problem-based learning can significantly impact students' critical thinking skills (Asghar et al., 2012; DeJarnette 2012; Duran & Sendag, 2012; Johns, 2012).

Teaching and learning difficulties have been reported in genetics resulting in unsatisfactory achievement (Agboghoroma & Oyovwi, 2015; Atilla, 2012; Williams et al., 2012). Abstract and multidisciplinary are among the major causes of learning difficulties. (Agboghoroma & Oyovwi, 2015; Atilla, 2012). Thus, iSTEMa is recommended because it is a multidisciplinary approach in nature and characterised by hands-on activities to make the abstract nature concrete. The literature on students' ability and academic achievement is inconclusive, hence the need for more study in this area.

# CHAPTER 3:

# CONCEPTUALIZATION OF THE STUDY

## 3.1 Introduction

Review of related literature on STEM components, integrated STEM approach, critical thinking skills, genetics and students' ability in chapter two, reinforces the research objectives in the first chapter. This chapter deals with the following: Theoretical framework, conceptual framework, the conceptualisation of STEM and preparation of integrated STEM instructional material (iSTEMim).

## 3.2 Theoretical Framework

The theories of learning do not offer solutions to the problem statement of the study, but rather draws the attention of the researchers to important variables in finding a solution (Merriam & Caffarella, 1999). Learning theories provide the direction of the research process. This study draws ideas from Vygotsky's Social Constructivist (Vygotsky, 1978)

### 3.2.1 Vygotsky's Social Constructivist Theory

The social constructivist theory highlights that learning or the construction of knowledge takes place in a social context (Vygotsky, 1978). He opined that students learn best when they are actively involved in the learning process. Students who are actively involved in their learning would interact with their physical surroundings and other individuals (social interactions) (Savery, 2006). Students' social interactions would lead to collective learning and the application of critical thinking skills (Powell & Kalina, 2009). The theory provides the basis for a paradigm shift from the traditional classroom model which is teacher-centred to a learner-centred model of instruction. Schreiber and Valle (2013) observed that knowledge construction by the students occur when students were active participants in the instructional process and not as passive receivers of information. The students and the teacher take up new roles; students take responsibility for their learning while the teachers acted as facilitators.

`Another aspect of the social constructivist theory is the concept of Zone Proximal Development (ZPD). ZPD can be summarised as:

> *The distance between the actual development level as determined by independent problem-solving and the level of potential development as determined through problem-solving under adult guidance or in collaboration with more capable peers* (Vygotsky, 1978).

ZPD explains the difference between a student's present level of achievement and his/her potential level of achievement. Therefore, for a student to achieve this potential level, Vygotsky stated that scaffolds are needed. The teachers must provide students with quality scaffolds or assistance to enhance learning and acquisition of relevant skills. Vygotsky advocated that active engagement in a social context (collaborative) should be used as a scaffold to assist students within their ZPD (Vygotsky, 1978). The theory emphasises students' mental engagement and the process of instruction and not on the final product. In support of this, it was reported that in constructivism, open-ended problem solving should serve as the basis for classroom instructional. (Gonen & Kocakaya, 2010).

Social constructivism provides the latitude for the integrated STEM approach (iSTEMa), and the features of this theory were used to prepare the integrated STEM instructional material also called iSTEMim. Deeper understanding and thinking skills are gained in iSTEMa through students' active engagement via activities such as hands-on, minds-on, questioning, generation of ideas in solving an open-ended problem (Bächtold, 2013). Consequently, Vygotsky social constructivist theory implies learning genetics through scaffolding.

According to him, low academic achievement is linked to students' passive involvement in classroom instruction (Darcy & Henderson, 2010). Consequently, literature has reported that instructional strategies that are characterised by students' active participation and social interaction have demonstrated achievement gains among low achievers (Aiyedun, 1995; Gambari et al., 2013a). Therefore, iSTEMim is designed based on Vygotsky social constructivist theory with the hope it will close the gap with regards to students' ability on achievement and critical thinking development.

This theory emphasises the scaffolding of instruction. Scaffolds are grouped into the Hard and Soft scaffold; the soft scaffold is on the spot guidance provided by the facilitator to the students during the instructional process, especially when students are confused and off tracts from the objective of the lesson. The facilitator will ask appropriate questions, and question prompts to bring them back on tract example of questions such as *what have you done? What do you think should be done next?* While hard scaffolds are supported that are prepared and integrated into the instructional approach to help learners achieve their potential. In this study, the hard scaffolds are the iSTEMim elements, the design worksheets, facilitator, and peers. For example, the design worksheet provides the driving question to guide the activities and in each phase.

The social constructivist environment could provide the scaffold for low achievers to engage in cognitive activities through interaction with high achievers. This concurs with Taber (2010) who highlighted that instruction based on social constructivist theory suits classroom instruction of students with different abilities.

At the ZPD, the facilitator drives the process of learning through asking relevant questions that will engage students' thinking and foster students' deeper learning so that the search for meaning becomes a personal endeavour for the students.

Example of driving questions to engage students' thinking such as; How do you come about that? Where can you get the required information? Researchers have reported that students' develop positive learning outcomes (increased interest, motivation, and academic achievement) and relevant skills when learners are meaningfully scaffolded in the learning process (Sinatra, Heddy, & Lombardi, 2015; Tytler & Osborne, 2012).

It is reported that instructional scaffolds enhance learners' independent learning and the development of critical thinking skills (Liu, Wivagg, Geurtz, Lee, & Chang, 2012). Related literature on instructional scaffolds indicated that scaffolds have significant effects on students' achievement than approaches that do not use scaffolds (Choo, Rotgans, Yew, & Schmidt, 2011; Hmelo-Silver, 2004). Probably because scaffolds help learners generate their ideas and understanding and engage their students' higher cognitive skills. Therefore, this theory provides the theoretical background for the integration of STEM while solving a genetic design problem in secondary schools.

### 3.2.2 The Link between iSTEMa and Social Constructivist Theory

The theory seems to provide support for the development of iSTEMim and the direction for the entire study. The elements of iSTEMa in this study were selected based on the social constructivist theory;

#### a Active engagement

The iSTEMa provided the activities and environment for students to be actively engaged during the learning. This was achieved through hands-on; experimentation, simulation of how traits are inherited by offspring from parents and engagement in a group project. Minds-on activities occur through students defining the problem, generating, justifying, and evaluating ideas.

b Learning is Student-centred

The learning process using iSTEMa is learner-centred; this is achieved through the iSTEMa iterative process which provides the latitude for students to navigate an instructional unit. The iSTEMa worksheets also provided a guide for self-directed learning. Therefore, the teacher acts as a facilitator providing prompts and classroom management to facilitate students' learning.

c Learning in a Social Context

The entire learning process is characterised by collaboration; students generate ideas individually and meet in a group to brainstorm their ideas to agree on the best idea. The students were group heterogeneously; mixed ability and gender. Therefore, peers will work collaboratively through peer tutoring, peer interaction and a group project to enhance each other's critical thinking skills.

The elements of iSTEMa will scaffolds students' thinking skills from lower order thinking (rote learning) to higher order thinking such as critical thinking and deepen students understanding in genetics. In line with this study, Lay and Osman (2018) reported that collaboration among peers and between students and the facilitator scaffolds students' deeper understanding and 21$^{st}$-century skills. The summary of the theoretical framework is as presented in Figure 3.1

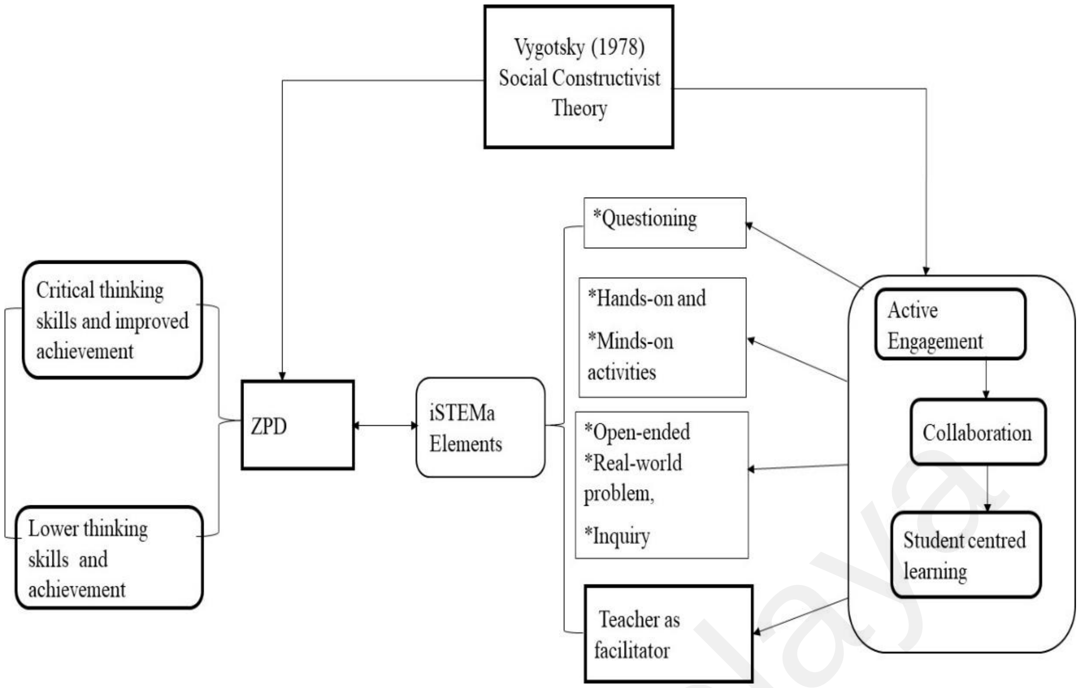


*Figure 3.1.* The link between iSTEMa and Constructivist Theory

Figure 3.1 shows the link between the elements of iSTEMa and social constructivism. The integration of science, technology, engineering, and mathematics to solve a problem is similar to the way STEM professional solve the problem in a real-world setting. In real-world settings, problems are multidisciplinary and professional work collaboratively to solve the problem. In summary, this study is build based on the constructivist learning environment. It is reported that the goal of a constructivist-based learning environment is to promote critical thinking skills, reasoning and self-directed learning (Demiral, 2018; Kwan & Wong, 2015). Therefore, this is consistent with the aim of this study which is to enhance learners critical thinking skills and students' achievement in genetics.

## 3.3 Conceptual Framework

A conceptual framework is the graphical or narrative illustration of the major constructs to be researched which are linked or connected to the research objectives (Miles & Huberman, 1994). The conceptual framework is built based on the related literature reviewed in chapter two on the primary variables of this research. It seeks to establish the relationship between the major variables of this study and highlight the research gap that exists in the literature.

### 3.3.1 Studies on Integrated STEM Education

Previous research findings reviewed in chapter two (2) have revealed the effectiveness of the integrated STEM approach in classroom instruction and the several methodologies were employed by researchers to implement STEM-based instruction (James, 2014; Olivarez, 2012; Sahin, Ayar, & Adiguzel, 2014; Thomas, 2013). Past research literature, methodology, and the dependent variable are highlighted in Table 3.1.

Table 3.1

*Past Studies on Integrated STEM-based Instruction*

| **Author/Year** | **Dependent Variable** | **Study Focus** |
|---|---|---|
| Brown et al. (2011) | Perception | Understanding STEM: current perceptions |
| Meyrick (2011) | Achievement | How STEM education improves learning |
| Stohlmann, Moore, McClelland, Roehrig 2011, | Perception | STEM integration program: Educators share experiences of STEM-base model |
| Wang, Moore, Roehrig, Park, (2011) | Perception | STEM integration Teacher perceptions and practice. |
| Thomas (2013) | Achievement | The effects of an integrated S.T.E.M. Curriculum in fourth-grade students' mathematics achievement and attitudes |
| Phonchaiya (2014) | Critical thinking skills | STEM-based instruction |
| James, J. S. (2014) | Achievement | Science, Technology, Engineering, and Mathematics (STEM) Curriculum and Seventh Grade Mathematics and Science Achievement. |
| Sahin, Ayar & Adiguzel (2014) | Achievement | STEM-Related After-School Program Activities and Associated Outcomes on Student Learning Educational Sciences |
| Robinson et al. 2014 | Achievement and process skills | STEM through problem-based inquiry on Gifted elementary students' science knowledge and process skills |
| Sampurno, Sari, & Wijaya (2015) | Disaster literacy | Integrating STEM (Science, Technology, Engineering, Mathematics) and Disaster (STEM-D) education for building students' disaster literacy |
| English and King (2015) | Design skills | Design-based learning: fourth-grade students' investigations in aerospace |
| Guzey et al. (2016) | Interest | Engineering design-based science |
| Shahali et al. (2017) | Interest | STEM through the engineering design process |
| Oosim & Champrasert (2017) | Critical thinking skills | Context-based STEM education among students in physics. |
| Lin et al. (2019) | Attitudes towards Technology | STEM inquiry-based activities |

In Table 3.1, it is observed that most of the studies focused on the effect of integrated STEM education on students' achievement in science as a dependent variable (Becker & Park, 2011; Robinson et al., 2014; Sahin et al., 2014; Thomas, 2013), students' interest (Guzey et al., 2016; Shahali et al., 2017), and attitudes (Lin et al., 2019). Previous studies also employ mostly content-based STEM integration (Laboy-Rush, 2011; Rockland et al., 2010; Wallace, Malone, Rennie, Budgen, & Venville, 2001). It would be observed from the Table that there was limited literature that focused on critical thinking skills as a dependent variable and no literature that focused on both the achievement and critical thinking skills. Secondly, the limited study adopted the engineering design process as a context for STEM integration. Therefore, this study focused on critical thinking skills and achievement as dependent variables

Previous literature has reported lack of instructional materials and expertise among teachers to implement the integrated STEM approach in the science classroom, which is an important gap that needs to be bridged (Abdu-Raheem, 2014; Kertil & Gurel, 2016; Olayinka, 2016; Roehrig et al., 2012). Because STEM approach is relatively a new approach to instruction and teachers are so used to the traditional instructional activities and will need guidance to implement STEM instructional approach (Stohlmann et al., 2012; Thibaut et al., 2018a). Therefore, the need to prepare iSTEMim and implement to achieve the research objectives.

### 3.3.2 Learning Difficulties in Genetics

In the past two decades, scholars have reported students' learning difficulties in genetic concepts (Atilla, 2012; Chu & Reid, 2012; Jalmo & Suwand, 2018; Lewis & Wood-Robinson, 2000; Mills Shaw et al., 2008; Tekkaya et al., 2001; Tsui & Treagust, 2010; Tsui & Treagust, 2002). This has resulted in the unsatisfactory achievement of students in genetics, and the reasons reported for the learning difficulties include; Abstract nature of genetics concepts and processes (Cimer, 2012; Knippels, Waarlo, and Boersma, 2005) and misconception of genetic concepts and principles (Tsui & Treagust, 2007)

Other reasons given are the multidisciplinary nature of genetics; apart from the science content, there is the mathematical (probability) content of Mendelian genetics (Awang-Kanak, Masnoddin, Matawali, Daud, & Jumat, 2016) poor instructional strategies such as traditional teaching method (Haambokoma, 2007; Tekkaya et al., 2001). Areas of learning difficulties are highlighted in Table 3. 2

Table 3.2

*Learning Difficulties in Genetics*

| **Author** | **Year** | **Contents Learners Found Difficult** |
|---|---|---|
| Lewis & Wood-Robinson, | 2000 | Genes, chromosomes, cell division, and inheritance |
| Saka et al | 2006 | Gene, DNA & chromosomes |
| Mills Shaw, et al | 2008 | Genes, chromosomes, and DNA |
| Dawson & Venville | 2009 | Genetic engineering |
| Tsui & Treagust | 2010 | Genetics |
| Atila | 2012 | Genetics |
| Chu, Y.-C., & Reid, N | 2012 | Genetics generally |
| Cimer | 2012 | Cell division, genes, and chromosomes |
| Williams et al | 2012 | Genetic inheritance and cell division |
| Mthethwa-Kunene et al | 2015 | Mendelian genetics (probability) |
| Awang-Kanak et al | 2016 | Basic Mendelian genetics |
| Jalmo and Suwand, | 2018 | Genetics generally |

Table 3.2 indicates that genetics is one of the essential science concepts that students struggle to learn worldwide (Chu & Reid, 2012; Mthethwa-Kunene et al.,

2015). It is observed that students' lack a conceptual understanding of genetics because teachers mostly employ instructional approaches which make students passive listeners. Researchers advocated alternative instructional strategies that are learner centred and emphasise hands-on activities to make the abstract nature of genetics concrete (Awang-Kanak et al., 2016; Mills Shaw et al., 2008). Hence the focus of genetics as an instructional content in this study

### 3.3.3 Students' Critical Thinking Skills (CTS) and Research Design

Literature has highlighted research in critical thinking skills. Table3.3 summarises the research design and focus of previous research on critical thinking.

Table 3.3

*Research in Critical Thinking Skills*

| Year | Author | Research Design | Focus |
|---|---|---|---|
| 2004 | Lombard, & Grosser | Quantitative | Survey of CTS among prospective educators |
| 2011 | Moore | Qualitative | Investigated the idea of CTS across three disciplines |
| 2012 | Shim, & Walcza, | Quantitative | Impact of faculty teaching practice on critical thinking skills (CTS) acquisition |
| 2012 | Pitan and Adedeji | Ex-post facto | Level of skill mismatch between what students acquire and labour market demand |
| 2013 | Chukwuyenum | Quantitative | Impact of CTS on mathematics achievement |
| 2013 | Ku, Ho, Hau, & Lai, E | Quantitative | Efficacy of modes of instruction on CTS achievement |
| 2012 | McDonald, G | Qualitative | Teaching critical and analytical thinking in high school |
| 2015 | Atabaki et al | Qualitative | The deductive categorisation was used to classify CTS in a conceptual framework |
| 2015 | Carvalho et al | Quantitative | Impact of real-life problem-solving on CTS |

Table 3.3 shows that in the last few decades, there are numerous researches on critical thinking skills (Atabaki et al., 2015; Ku et al., 2014; Lombard & Grosser, 2004;

Moore, 2011; Tsui 1999). Several researchers have highlighted the importance of critical thinking for meaningful living and to compete favourably in the 21st-century global market (Chukwuyenum, 2013; Kivunja, 2015; Sada et al., 2016). Most of the empirical literature did not focus on STEM-based integrated instruction and critical thinking skills

The lack of critical thinking skills among students is known to exist at all levels of education worldwide (Demiral, 2018; Jatmiko et al., 2018). Nationally, it is reported that students in Nigeria are deficient in critical thinking skills (Sada et al., 2016). Internationally, the lack of critical thinking is reported in Indonesia (Saputri et al., 2019), United States of America (Marin & Halpern, 2011) and Dubai (Taleb & Chadwick, 2016).

Therefore, iSTEMa is proposed as an approach to help learners develop critical thinking skills. The iSTEMa is made up of phases; the engaging problem, generation of ideas, application of ideas to problem-solving, evaluation and redesign and communication of findings. It is expected that this approach will help engage in meaningful learning through active engagement such as hands-on activities and group interaction.

One of the important features of iSTEMa material is the use of algebraic thinking to illustrate the rules of genetic combination (genotype) that will give rise to a given phenotype expression (phenotype). "Algebraic thinking is used to examine scientific data and predict the effect of change of one variable on another" (the NGSS Lead States, 2013) The relationship between the independent and dependent variable in the conceptual framework are highlighted below in Figure 3.3

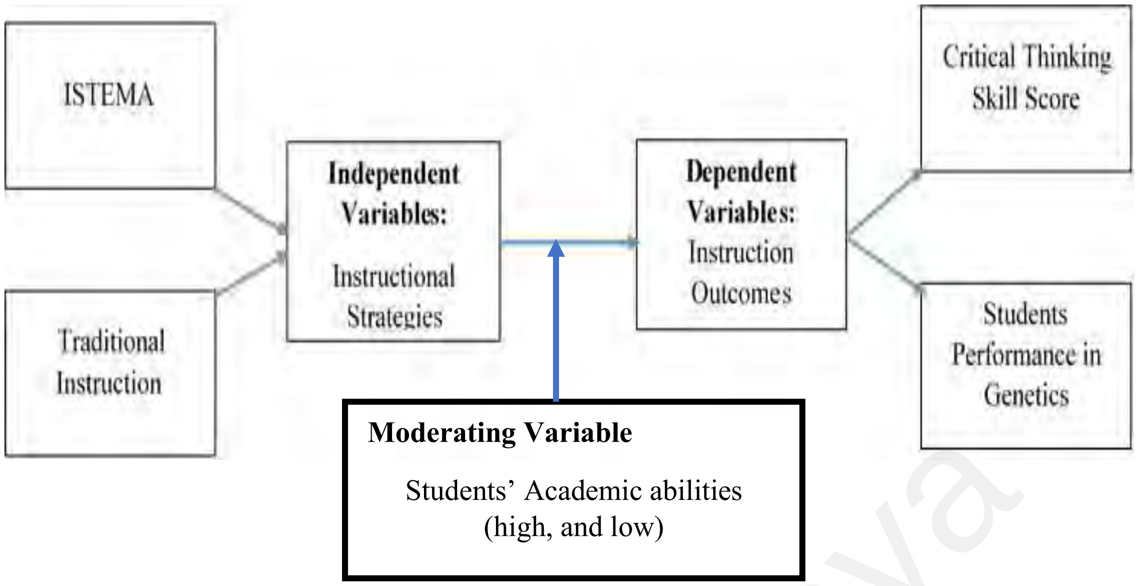


*Figure 3.2 Conceptual Relationship between the Variables*

The conceptual relationship as illustrated in the figure show that the independent variables in this study are the iSTEMa and traditional teaching method which factors that were manipulated to determine their effects on the dependent variable. The dependent variable are critical thinking skills and students' achievement in genetics. Furthermore, the moderating variable is students' academic ability which have been highlighted to influence students' achievement in chapter two.

**Conceptualisation of iSTEMa**

There is a consensus among researchers that integrated STEM Approach provides the learning context where students actively engage in the learning process to acquire relevant skills such as critical thinking and promote achievement which the traditional instructional model cannot provide. However, there is no consensus on the definition of STEM-based instruction (Herschbach, 2011; Thibaut et al., 2018a).

Among several definitions, Kennedy and Odell (2014) and Roberts (2012) define STEM education as an integrated instructional approach that removes the traditional barriers between the STEM disciplines to facilitate the transfer of knowledge from one discipline to the other. Similarly, Sanders (2009) sees integrated STEM education as an instructional process that involves two or more STEM subjects. He sees integrated STEM as a pedagogical approach of employing engineering design and scientific inquiry which is based on the constructivist learning theory. While Moore and Smith (2014) highlighted that integrated STEM approach requires students to engage in the engineering design process through the integration or application of science and mathematics concepts. Guzey et al. (2016) accentuate that engineering is a meaningful link to science and mathematics and enhances the meaningful learning of science and mathematics. Therefore, the definition of Moore and Smith (2014) is adopted for this study; students will engage in science through the engineering design process and integrate scientific knowledge to solve the problem and engage in critical thinking.

## 3.4 Engineering Design Process.

This is a design-based problem-solving iterative process. Purzer and Shelley (2018) reported that the integration of STEM discipline could best be achieved through the engineering design process. They believe that engineering is a natural integrator of science and mathematics because it is a multidisciplinary problem-solving process.

Engineering provides a better platform for the application of mathematics' and science like the way professional work in real-life because it is a problem solving iterative process (Carr & Strobel, 2011; Gallant, 2011; Sanders, 2009; Thibaut, Knipprath, Dehaene, & Depaepe, 2018b). Research studies have documented the advantage of secondary school students' participating in the engineering design process to include improved learning achievement and positive attitudes towards STEM (Shahali et al., 2017; Wendell & Rogers, 2013). However, there is limited integration of engineering into classroom learning in secondary schools (English & King, 2015). This could be because of mathematics and science textbook focus on learning facts and concepts instead of the application of these concepts and facts or ideas to problem-solving (Garrison, 2004; Riskowski, Todd, Wee, Dark, & Harbor, 2009). In many countries especially in Nigeria, the engineering design process is not accorded the much-needed attention it deserved in STEM classroom instruction.

The number of engineering design phases have severally been implemented by scholars depending on the students' educational level; English and King (2018) adopted a six-phased engineering design process; problem raising, ideas generation, designing and constructing a prototype, testing prototype, redesigning and reflecting and communicating findings. The study was conducted among $6^{th}$-grade students, and the findings indicated that the students demonstrated the application of mathematics and science knowledge. Rauf, Rasul, Sathasivam, and Rahim (2017) reported that STEM instruction should be implemented using the engineering design process. In their study, the engineering design process was implemented using a five-phased iterative process which includes Imagine – Design – Create – Test and Improved (Rauf et al., 2017). Their study focused on an initiative for STEM education in primary schools, through training of science teachers on STEM education implementation. The findings show teachers readiness and confidence to implement STEM instruction in primary schools. The phases of Imagine – Design – Create – Test and Improved are most peculiar to the primary level of education. The similarities in the engineering design phases mention above is that both scholars focused on designing a prototype.

Similarly, English and King (2015) implemented the following phases among elementary school students; problem scooping, idea generation, design and construct, Evaluation and redesign. Their study focused on STEM learning through Engineering design among 4th-grade students. The findings show that 4th-grade students successfully integrated science and mathematics using the engineering design process. They concluded that young learners could engage in STEM instruction using the engineering design process.

Engineering design process has also been implemented using a learning cycle such as; Ask, Imagine, Plan, Create and Improve which was implemented among middle, secondary school students (Shahali et al., 2017). In this study, the students **Ask** to understand the problem, **imagine** the solution, develop a **plan** to solve the problem, **create** the solution and improve the solution or prototype. Shahali et al. (2017) focused on middle secondary school students' interest in STEM subjects and careers; the students participated in STEM learning approach through a five-phased engineering design process (Ask, Imagine, Plan, Create, Improve). Using a pre and post-test, the findings show a significant mean increase in students' interest in STEM subjects from moderate to high.

A five-phased cycle of Identify problem, brainstorm, develop an idea, create a plan, develop and test the prototype, improves prototype was adopted by (Lottero-Perdue, Roland, Turner, & Pettitt, 2013). While Think, make and improve (Martinez & Stager, 2013). Mangold and Robinson (2013) adopted an eight-phased engineering process; define the problem, research problem, collaborate on the solution, analyse the solution, select the best solution, design prototype, test prototype, and redesign. These eight-phased process was design by the authors to engage students in both problem and project based learning. This implies that students search for solution to the problem in the first four stages (define the problem, research problem, collaborate on the solution, analyse the solution, select the best solution) as problem-based learning. They students proceed to build and evaluate the prototype (design prototype, test prototype, and redesign) as project-based learning. Mangold and Robinson (2013) adopted a qualitative method and findings indicated that both students and teachers express satisfaction in engaging in solving the problem using the process. The students also demonstrated an understanding of the concepts of engineering.

Given the proceeding, there is consensus that the engineering design process provide the platform for student to engage in real-life and open-ended problem solving which will culminate in students developing a solution or a prototype. Fundamentally, in the process allow students to engage in meaningful learning of science and mathematics. However, there seems to be no consensus on the number of phases to adopted because while others adopted 3, 4, 5 or 6 phases. Others adopted eight phases of engineering design process.

In this present study, a five-phased engineering iterative process was adopted because it will provide the platform to apply or integrate science (genetics) and mathematics (probability) to solve the open-ended problem. The iterative nature of the engineering design process will provide the basis for self-regulated learning and engages students' higher cognitive abilities. The phases adopted based on experts' consensus include; the Engaging problem, Generation of ideas, Design solution, Evaluation and improve and Communication of findings. In this study the phase of test prototype and redesign is combined into one phase evaluation and improve; this is because we are dealing with biological phenomena the final output could be a product or process. These phases provided the latitudes for the application of genetic knowledge (dominance, recessive, phenotype, genotype among others) to design an imaginary genetic modified organism This is illustrated in the figure below;

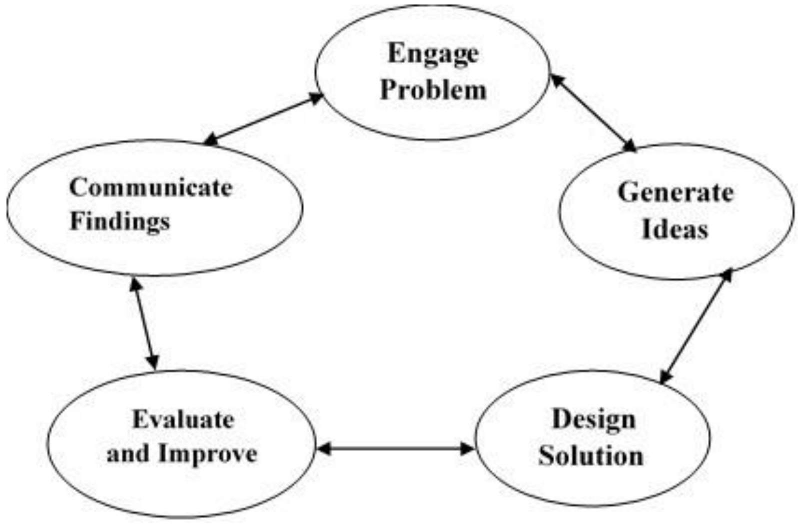


*Figure 3.3. iSTEMim Design Phases Adopted from English and King (2016)*

There natural a link between science and engineering because science principles and concepts and applied in designing engineering solutions. Therefore, it was observed that students could gain conceptual understanding of scientific concept if they link the goal of engineering to science learning (Siter, Klahr, & Matlen, 2013). Nevertheless, Guzey et al. (2017a) contended that if the integration of engineering design process fails to underpin or support the integration and meaningful learning of science, the entire process can be seen as a mere crafts project. To this end, there is a need for a better way to integrate engineering to maximise its potential in enhancing learning outcomes.

### 3.4.1 Integration of the Engineering Design Process

There are several ways to use engineering as a context to integrate science and mathematics. Three types have been identified in the literature; add-on or culminating project, implicit engineering integration and explicit engineering integration (Crotty et al., 2017; Guzey et al., 2017a). In add-on engineering integration students learn science unit and employ engineering at the end as a culminating project. In this method, the connection between science and engineering may not be apparent (Dare et al., 2018; Guzey et al., 2017b). In implicit integration, the instructional unit is situated with engineering at the beginning followed by other parts of the unit of science instruction and at the end engineering design process is revisited (Crotty et al., 2017). The explicit integration involves teaching and learning a science unit through the engineering design process. This approach provides the learner with the opportunity to engage in science and engineering practices (Dare et al., 2018; Guzey et al., 2017b). In this study, the engineering design process is explicitly integrated to serve as a context to integrate science (genetic concepts) and mathematics (probability and algebraic thinking). Guzey et al. (2017b) reported achievement gains in science achievement using explicit engineering integration. There seem to be limited studies linking explicit engineering integration of STEM education with critical thinking skills.

It was reported that, the benefit of integrating engineering as a component of STEM in secondary schools will improve students' achievement in science and mathematics and create the awareness of engineering design process as well as enhance students' literacy in technology (Katehi, Pearson, & Feder, 2009; Stohlmann et al., 2012). Other literature advocated for engineering to be integrated as Engineering Design Process (EDP) to increase students' active exploration (search for relevant ideas from different sources) of the instructional unit, assist learners gain positive attitudes towards science learning, and improve science learning (National Academy of Engineers & National Research Council, 2009; Wendell & Rogers, 2013).

## 3.5 Context Model of Integration

The integrated STEM education is an evolving paradigm with different dimension to its implementation in the classroom, Roehrig et al. (2012) categorised integrated STEM-based instruction into two models which are content integration and context integration. The STEM content model of integration involves more than one instructional content from STEM disciplines are involved or covered. This implies that in a unit of instruction the learning objectives of the content of two or more disciplines are involved, example learning content of science and engineering (Kanadlı, 2019). The learning outcomes will be measured based on the content of the subjects involved in the integration (Honey et al., 2014; Kanadlı, 2019).

On the other hand, the context model of integration is adopting the teaching of the content of one discipline and selecting the appropriate practices and concepts from the other discipline to enhance the learning of that subject matter (Dugger, 2010; Kertil & Gurel, 2016). In support of the context model of instruction, it was observed that science and mathematics should be given, the principal role, while technology and engineering serve complementary roles to learn mathematics and science (Corlu et al., 2014). This implies focusing on the topic of one subject at the centre and choosing appropriate practices and processes from STEM subject areas or disciplines to enhance learning and acquisition of critical thinking skills (Kanadlı, 2019; Kertil & Gurel, 2016). Context-based STEM Integration involves using engineering design as a scaffold to teach and learn the content of mathematics and science discipline.

Given the proceeding, this study adopted the context model STEM integration in this research. This is because the Nigerian educational system is rigidly structured for the teaching of a single subject and are entirely compartmentalised in a traditional setting. This implies that the context model of integration was more appropriate to the present school system in Nigeria. Therefore, science concept (genetics) was the central focus while mathematics, technology, and engineering practices were used to deepen the understanding of genetics and help students acquire critical thinking skills. In support of this, Kertil and Gurel (2016) observe that in the rigid traditional school system, a context-based model of STEM integration is more appropriate with regards to the learner, teacher, and the administrator. The genetic problem, therefore, was the focus, students will collaborate to define, investigate and generate ideas, apply the best idea to solve the problem and communicate their findings.

In this study, some of the achievement expectations in the NGSS that are relevant to the achievement expectations of the biology syllabus in Nigeria were adapted for example;

i. The use of diagrams to explain variation in offspring genotype resulting from sexual reproduction, using representations such as Punnett squares and diagram to explain the cause and effect in the transmission of traits from parents to offspring which results in variation.

ii. Apply the mathematical concepts of probability and statistics to describe the distribution of phenotypes or observed characters in the population and defend the assertion that genetic variation may result from the new genetic combination between the parents (Cox, Reynolds, Schuchardt, & Schunn, 2016a; the NGSS Lead States, 2013)

Therefore, it is hoped that this approach will help learners acquire critical thinking skills and deepen the understanding of the genetic concept in biology, and help learners see the connection between these disciplines in problem-solving in real life.

## 3.6 Preparation of iSTEMa Instructional Material

This section discusses the preparation of iSTEMa instructional material. This is to answer research question one (what are the elements embedded in iSTEMa instructional material that could enhance critical thinking skills and genetic achievement?). This will help to provide a guide on how to teach and learn genetics and help students acquire critical thinking skills. It is important to note that there are several models for the development of instructional and training materials. Some of the models include; the Kemp's Design Model (1985), Dick and Carey (2004) among others as highlighted in chapter 2. However, most of these model was based on the ADDIE model (Kruse, 2009). In this research study, the researcher adapted the five-phases model; Analysis, Design, Development Implementation and Evluation (ADDIE) for the preparation of the instructional material.

### 3.6.1 ADDIE Model

The ADDIE was developed by the Educational technology centre, Florida State University (Watson, 1981). Morrison (2010) see ADDIE as a framework that provides the generic stages and process used by researchers to develop instructional materials and training manual. Each phase of ADDIE manual has specifically defined activities that are to be performed as highlighted below

#### a Analysis Phase

This is also called a need analysis phase which requires the designer to identify the instructional goals, and objectives. The target audience, learners' knowledge and competencies are identified. The need analysis could be established through qualitative data collection strategies; literature review, interviews, documents analysis and quantitatively through the use of questionnaires. The finding of need analysis provides the foundation for the design phase.

b Design Phase

This phase is built with regards to the findings of needs analysis with particular regards to the goals and objectives of instructional material. Therefore, this phase involves determining the components and elements to be embedded such as; instructional activities, instructional approach, lesson planning and method of assessment, among others. At this phase, a draft of the instructional material is developed. Since one of the objectives in this study is to assist learners to acquire critical thinking skills, the activities, approach and materials must to selected to achieve this objective.

c Development Phase

This involves formative evaluation or validation of the draft instructional material or module by experts in the field; in this study, it was science education experts. The element established at the design stage is validated to achieve experts' consensus. This could be done online or by face to face. The module or instructional material was validated severally. Experts comment and observations are used to improve the instructional materials. The developed instructional materials are further pilot tested

d Implementation Phase

At this stage, the implementational material is delivered to the target audience (learners). It can also be seen as the implementation of the instructional approach, content and activities in the classroom among the students. The researcher collects data to determine the instructional approach and activities are delivered correctly, identify lapses between the goal of the instructional materials and the actual implementation that could be corrected.

e Evaluation Phase

The learners are evaluated to determine the effectiveness of the developed I.M. Evaluation should include a formative and sensitive evaluation. During this phase, data can be collected quantitatively and qualitatively or both to assess the effectiveness of the instructional materials

Table 3.4:

***Summary of ADDIE, Method of Data Collection and Purpose***

| Preparatory Phases | Collection of Data | Basic purpose |
|---|---|---|
| Needs Analysis | Documents analysis and interviews and questionnaires | To establish the need for the instructional material and gap it will seek to bridge |
| Design | Gathering of essential and relevant information through literature review and documents analysis | Established the components and elements of the instructional material; the purpose of the study, objectives, contents, and activities. The draft copy of the instructional materials |
| Development | Quantitative (Likert type questionnaires) and Qualitative (open-ended questions) | Validation of instructional material using questionnaires for organisation, readability and collection experts' inputs, comments, and recommendations through open questions to improve the product |
| Implementation | Identification of issues to be corrected | The completed instructional material is implemented among the target population senior secondary school using a mixed-method |
| Evaluation | Mixed method, quantitative or qualitative | The effects of the instructional material on students' learning outcome |

### 3.6.2 Need Analysis

In this phase the instructional goals, target audience and learners' prior knowledge and environment were identified. The target audience were senior secondary school students' class 2 (SSII) or equivalent to Year 11, and their average age is 15 years. The need analysis was undertaken to establish if there were inconsistencies between the goal of science instruction as enshrine in the educational policy and classroom practices. In other words, to establish whether there is an essential gap or need to prepare iSTEMim. The data for need analysis came from three sources: literature review, document analysis; policy document and textbooks, and interviews of teachers.

### 3.6.3 Findings from Need Analysis

The findings from need analysis were highlighted based on the source of the data; literature review, document analysis, interviews and questionnaires;

#### a Literature Review

The findings from related literature review highlighted the following; the traditional instructional learning environment which does not enhance meaningful learning dominates the Nigerian classroom (Akintunde, 2018; Audu, 2018; Gambari et al., 2013b). Literature has advocated for rebranding or a paradigm shift of educational practices through the implementation of innovative instructional strategies such as integrated STEM-based instruction that will facilitate meaningful learning and thinking skills (Audu, 2018; Gimba et al., 2018). Nevertheless, there is lack of instructional materials for the implementation of innovative instructional strategies (Aibuedefe & Tina, 2017; Anugwo, 2015; Kola, 2013; Nadelson et al., 2013; Olayinka, 2016). The literature shows the need for a paradigm shift in classroom instruction such as integrated STEM-based instructional approach and the need to develop instructional materials.

#### b Document Analysis

The assessment of the relevant document was done based on the researcher's analysis. A critical observation of the National Policy of Education in Nigeria (NPE) to identify policy statements relevant to this research study and to compare it to science instruction and instructional materials available. One of the goals includes

> *the acquisition of appropriate skills and the development of mental, physical and social abilities and competencies as equipment for the individual to live in and contribute to the development of the society (Federal Republic of Nigeria, 2004, P32).*

Worthy of note, it was stated that

> *science and technology shall continue to be taught in an integrated manner in the schools to promote, in students the appreciation of the practical application of basic ideas (Federal Republic of Nigeria, 2004, P32)*

Observation of the science instructional materials, especially biology textbooks, schemes of work and syllabus, the researcher found that most of the relevant instructional materials in biology are science content based. Textbooks do not highlight how teachers will assist learners in acquiring higher order thinking skills, but instead, focus on the content of the subject. Mathematics and science textbook focus on learning facts and concepts instead of the integration of these concepts and facts or ideas to problem-solving (Garrison, 2004; Riskowski et al., 2009). The textbooks of each STEM discipline are written in isolation without linking it to another STEM discipline as established from documents analysis. This is mirrored in the lack of mathematics integration in science manuals and textbooks. Therefore, these subjects are taught as abstract concepts without applying them to evident processes (Cox, Reynolds, Schunn, & Schuchardt, 2016b).

Therefore, instructional materials are not in line with the policy statement which states that science instruction should be in an integrated manner and helping learners acquire appropriate skills (critical thinking, problem-solving and collaborative skills). This finding agrees with the assertion that instructional materials are not available in Nigerian schools leading to traditional modes of instruction and poor achievement (Abdu-Raheem, 2014; Olayinka, 2016). Furthermore, the science curriculum does not take into account students' real-life or daily experiences, and science content and instruction is not linked to how students could solve problems in real-life.

### c Interviews

Teachers were interviewed on their current practices in classroom instruction, and some of the major aspects that emerged from the data include; lack of expertise to implement integrated instructions, lack of instructional materials and rigid school curriculum and school system. These major categories seem to suggest that there is a gap that needs to be bridged with regards to integrated STEM implementation in the classroom.

Teachers' responses seem to lack the knowledge and expertise to implement innovative instructional materials such as integrated STEM-based approach and therefore stick to traditional instructional practices as indicated in the following excerpts.

> *Changing from the present method of teaching (traditional method) to the modern method of teaching like the one you mentioned (integrated STEM) could be a welcome idea, but we do not know how to go about it*
>
> *(Waziri, !5th January 2016*
>
> *My lessons every day follow a definite pattern; introduce the lesson, present the lesson and ask students question base on what they have learned and summarise the main points of the lesson. I do not seem to figure out how to implement other methods of teaching*
>
> *(Isiaka, 15th/01/2016)*

Another teacher narrated his typical lesson which seems to mirror the traditional instructional method as presented in the excerpts below

> *In the classroom, the students listen attentively while I introduce the lesson by explaining the main points of the previous lesson, proceed to implement the lesson while students listen attentively and ask questions where there is*

*confusion. At the end of the lessons, I evaluate students understanding by asking questions based on the specific objectives of the lesson*

*(Thehnum,16th/01/2016).*

Teachers also express the lack of instructional materials and framework to guide them to implement instructional approaches that will promote meaningful learning. The available instructional materials are traditionally based as indicated in the following excerpts.

*The instructional materials provided by the school, subject recommended textbooks provided by the school and my lesson notes, sometimes, I draw diagrams on a cardboard paper to illustrate to the students what I am teaching them, and no instructional guide to implementing other new methods even though we are encouraged to adopt new methods of teaching*

*(Wyong, 15th/01/2016)*

Another respondent highlighted;

*I teach biology; the students have the recommended textbooks. I go through the examples with them and ask the students to solve some exercises and submit their notebooks for marking. The main instructional material is the biology recommended textbooks that are available for use.*

*(Gban, 15th/01/2016)*

*..... for me sometimes we are helpless in the classroom because there are no modern teaching materials to teach hmm.. we make do with what is available. You may want to check our science laboratories*

*(Bello 16/01/2016)*

This implies that there are no instructional materials to implement innovative strategies, and so teachers hold unto traditional instructional practices.

Secondly, from the researcher's personal experience; He had his primary and secondary education as well as his first and second degrees in Nigeria. He was taught with traditional lecture methods, the teachers used the talk and chalkboard, and notes were written on the blackboard for students to copy. It is unfortunate to observe that during this need analysis nothing has changed d Experts Consensus on Need Analysis

Quantitatively data was collected using questionnaires from experts during need analysis to support the findings from interviews and document analysis. Okoli and Pawlowski (2004) reported that 10-18 experts are appropriate during design and development research to achieve experts' consensus. They maintained that the experts could be anonymous to each other and do not have to meet face to face. Similarly, it was reported that 10 to 50 could be satisfactory to achieve consensus using the Delphi technique (Jones & Twiss, 1978). In this study ten (10) experts were used, 60% of the experts were males, and 40% were females. The questionnaire was used to find the opinion of experts on the need to develop the iSTEMa instructional material. Each item of the questionnaire is made up of a statement of need with adapted Likert type of scale grading; Strongly Accepted (4), Accepted (3), Not Accepted (2) and Strongly Not Accepted (1).

The findings indicated that an average of 90% experts strongly accepted while 10% accepted that there is the need to develop the instructional material. This indicates that all experts accepted that there is a need for iSTEMa instructional material (iSTEMim). This finding agrees with Kasim and Ahmad (2018) who reported that the percentage of experts' consensus should be 75% and above. The findings corroborated the results from the literature review and interviews that indicated a lack of expertise and instructional materials to implement STEM-based instructions. Therefore, the researcher proceeded with the design and development of the instructional materials.

### 3.6.4 Design Phase

The design phase deals with planning the instruction by selecting the appropriate activities, media and strategies for the content and the criteria for proper assessment. The learning objectives are one of the important aspects of the design phase (Hattie, 2012). Therefore, based on the results of the needs analysis, the goal and objectives of the instructional materials were established. These are attitudes, skills and knowledge (OECD., 2018) students are expected to acquire after using the iSTEMim. The is followed by a selection of instructional elements, strategies and task to achieve the objectives. The components of the instructional materials are as highlighted in Table 3.5

*Table 3.5*

*Components of iSTEMim*

| Components | Description |
|---|---|
| Title | Integrated STEM instructional material (iSTEMim) |
| Learning Objectives | These are performance objectives that learners could acquire at the end of learning with the iSTEMim |
| Instructional Elements | These instructional elements adapted to be embedded in the instructional material to engage learners' higher cognitive skills |
| Instructional Phases | These are phases adopted from the engineering design process to provide the context to learn science and enhance critical thinking skills |
| Instructional Task | These are the design-based learning task included to help learners learn genetics and acquire critical thinking skills |

**Learning Objectives**

For an instructional material to be adopted by experts for classroom instruction, The instructional material should be linked to national education standards and local needs (McFadden & Roehrig, 2017). Therefore, the learning goal and objectives were drawn based on national education standards and the principles of integrated STEM education. The proposed performance objectives include;

- Enhance their critical thinking skills (inference, recognising assumption, deduction, interpretation and evaluation)

- Apply and integrate STEM learning content and principles, plan and carry out scientific investigation
- Enhance students' genetic learning and achievement (explain Mendel's laws, concepts and terminology)
- Use proportions, percentages and ratios to solve problems
- Explain the concept of Dominance and Recessive Trait
- Identify and practice an iterative process of designing a solution through the engineering design process.
- Identify the relevance of STEM to their daily lives.
- Construct an evidence-based explanation and solution
- Define the problem and generate ideas
- Enhanced collaborative skills.
- Enhance students' motivation and learning satisfaction

Given the above performance objectives, instructional elements were carefully selected from the literature review to be embedded in the iSTEMim to achieve the learning objectives. During this phase, 12 instructional elements were proposed which includes; 1) Open-ended problem, 2) Real world scenario 3) Questioning, 4) Hands-on activities 5) Minds-on activities, 6) Inquiry 7) Collaboration, 8) Authentic task, 9) Argumentation 10) Group projects, 11) Authentic assessment and 12) Teacher as facilitator (Treacy & O'donughue, 2014; Fortus et al, 2005; Stohlmann et al, 2012; Bybee, 2010; Sampruno et al, 2015).

After an extensive literature review, seven iterative engineering design phases were proposed as the instructional context; 1) engaging problem, 2) generation of ideas, 3) brainstorm, 4) designing prototype, 5) testing prototype, 6) redesign and 7) communicate findings. Four tasks were proposed; 1) engineering a unique hare, 2) moth insect for the aesthetic value an, 3) “Black + Black = Black”, and 4) paternity disputes. These proposed elements of each component were subjected to formative evaluation through two rounds of experts’ consensus survey in the next phase.

### 3.6.5 Development Phase

This phase involves formative evaluation to increase and established the likelihood that the iSTEMim will achieve the stated performance objectives. The evaluation of teaching materials at this stage is done to refine the learning materials components and make it ready for final validation (Nisa, Jatmiko, & Koestiari, 2018). Experts comments and observation from the formative evaluation was used to improve the quality of the iSTEMim. The procedures of the formative evaluation of the iSTEMim are highlighted in Figure 3.4

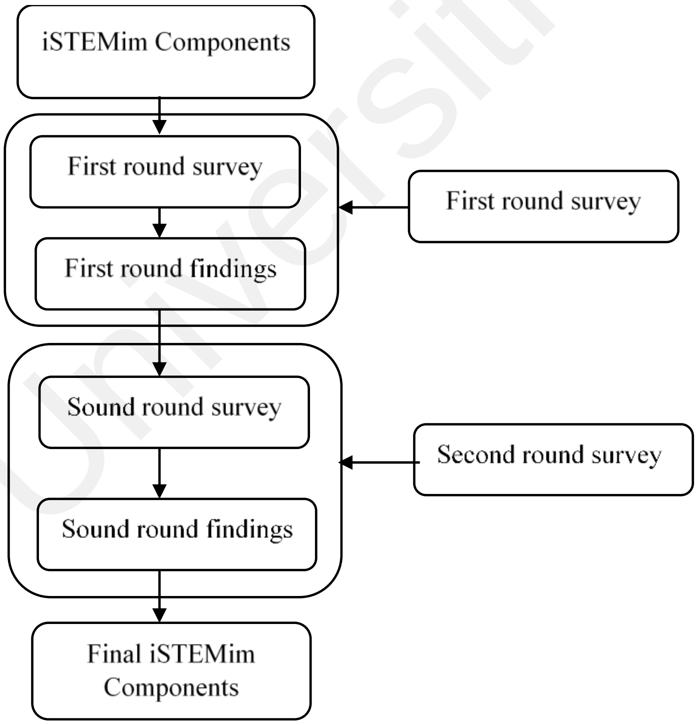


*Figure 3.4. Flow Chart of the Development Phase*

The formative evaluation of this module involves three stages; using a checklist to establish the important components of the iSTEMim, validation of the instructional material by science education experts for face and content validity. Finally, a micro-evaluation of the module is carried out among the target users for both students and teachers. Experts give their opinion on the prototype.

#### a First Round Survey

This carried out by science education experts to determine whether the items of each element are relevant to be included in the instructional materials. Therefore, a checklist of the components was sent to the experts, against each item, the experts are to agree or disagree by selecting (√) the right response. A score of one (1) is assigned for the relevant item while zero (0) for an item that is not relevant (Abualrob & Daniel, 2013; Kristanto, Mustaji, & Mariono, 2017). In the first-round 15 learning objectives, 12 instructional elements, seven learning phases (iSTEMim phases) and 4 instructional tasks which were highlighted during the design phase were sent for first of round experts survey. Twelve science education experts were involved in the first-round survey while 10 experts participated in the second-round survey.

#### b Findings from the First Round Survey

The data was analysed using a simple percentage. The items in each component with a percentage score of 70% and above were retained while items below 70% were eliminated. The findings after the first round showed that 7 learning objectives, 7 elements, 5 iterative cycles and 3 tasks received experts' consensus and were retained. These components and their elements were subjected to the second round of survey for experts' agreement.

c Second Round Survey

The items of each component retained through experts' consensus in round one (1) are subjected to second round experts survey. In this second round, 10 science education experts were involved. The findings of the second round of the experts' consensus indicate that the 7 learning objectives were accepted by experts for inclusion in the instructional material. Similarly, after the first and second survey the components, the experts agreed on 6 elements, 5 instructional phases and 3 tasks to be included in the iSTEMim as presented in Table3.6

*Table 3.6*

*Experts Consensus on the items of each component*

| Component | Items | % of experts' consensus |
|---|---|---|
| Learning Objectives | Students were able to demonstrate inference, recognition of assumption, deduction, interpretation and evaluation | 90% |
| | Explain Mendel's laws, identify and explain genetic terminologies; homozygous, heterozygous, alleles, phenotype, genotype, dihybrid among others | 100% |
| | Use proportions, percentages and ratios to solve problems | 100% |
| | Explain the concept of dominance and recessive trait | 100% |
| | Identify and practice an iterative process of designing a solution through the engineering design process. | 90% |
| | Integrate science and mathematics to solve the problem | 90% |
| | Enhance students' motivation and learning satisfaction | 80% |
| Instructional Elements | Open-ended problem | 90% |
| | Real-world problem | 80% |
| | Questioning | 80% |
| | Hands-on activities | 100% |
| | Minds-on activities | 100% |
| | Inquiry | 90% |
| Instructional Phases | Engaging the problem | 100% |
| | Generate ideas | 90% |
| | Design solution | 90% |
| | Evaluate and Improved | 90% |
| | Communicate findings | 100% |
| Learning Task | Engineering a unique savannah hare that will benefit the community | 100% |
| | Creating an insect for aesthetic value in a community that insects are valued | 90% |
| | Settling a family dispute on the appearance of a new trait | 7 |

## 3.7 Validation of the final iSTEMim

The second part of the development phase is the validation of iSTEMim. This is done to establish whether the instructional material will serve the intended purpose (Fraenkel & Wallen, 2007) and identify areas that need further improvement. Ten science education experts participated in the content validity and practicability of the iSTEMim. The questionnaire used for the validation was Likert-type with a grading system of Strongly Agree (4) Agree (3), Disagree (2) and Strongly Disagree (1). The iSTEMim instructional material is further evaluated for practicability among senior secondary school students that are part of the population but not part of the sample for the study.

### 3.7.1 Experts Validity of the Content of iSTEMim

The content validity of the instructional material is carried out with the view to meet the following criteria; appropriate for the target population, improve students' learning outcomes targeted, enhance positive attitudes towards learning and method of implementation of the instructional material is satisfactory (Kasim & Ahmad, 2018). Content validity involves measuring the content of the instructional material while face validity measures the concept being studied (Fraenkel & Wallen, 2007).

The questionnaires were developed using guidelines for product planning or instructional materials (Dick, Carey, & Carey, 2005; Seels & Glasgow, 1998). The guidelines include; the language use should be clear and not ambiguous or vague, items should be logically arranged, and the length of items should not be too long. Similarly, Seels and Glasgow (1998) provide lists of question that should be answered at each phase, for example in need analysis phase, question to be answered include; what is the need? What is the instructional content and characteristics of the population? Based on these questions the questionnaires will be developed to generate data that can provide answers to these questions. The guidelines involve drawing the list of relevant information; Need analysis question where the items focus on the need to develop the instructional materials. The design phase focused on the elements to be embedded in the instructional material; specifically, elements that can engage learners' critical thinking skills such as questioning, hands-on and minds-on activities among others

The questionnaires were Likert type; strongly agree, agree, disagree and strongly disagree which were reviewed by experts and found suitable. The result of experts' validation of the content of the iSTEMim which includes the performance objectives, instructional elements, activities, phases and tasks. The findings of experts' validation indicate the number of experts and their percentage that either agrees or strongly agree. The example in the first item all the ten (10) experts (100%) strongly agree that the purpose of the instructional material was clearly stated. The findings indicated that an average of 75.38% of the experts strongly agree, while 24.62% agree that the content of the instructional material was satisfactory. This finding agrees with Kasim and Ahmad (2018) who reported that experts' consensus should be 75% and above. Hence, the content of iSTEMa instructional material was valid.

### 3.7.2 Findings on the Practicability of iSTEMim

The completed and final copy of iSTEMim was further evaluated by experts to determine its practicability; this implies the iSTEMim can be put into practice, or it is usable. The finding of experts' validation on the practicability of iSTEMim. The number of experts and their percentage for each statement of strongly agree or agree is indicated. The overall results practicability of the instructional material indicated that 80% of the respondents strongly agreed, while 20% of the respondents agree that the instructional material was practicable. This finding agrees with Kasim and Ahmad

(2018) who reported that the percentage of experts' consensus should be 75% and above. Hence experts' consensus on the content of iSTEMim was achieved.

### 3.7.3 Experts Comments and Observation

Some of the observation of the experts during the validation includes: "*Need to pilot test the instructional material with the target audience to determine whether the language and the entire module is appropriate for the students.*" Another expert remarked that *"the module was well designed and it seems to have the potential to enhance meaningful learning and students' ability to think critically."*

Experts comments and suggestions were used to improve the iSTEMim. Example of the suggestion and researchers' action is highlighted in Table 3.7

Table 3.7

*Experts Comments, Suggestions and Researchers' Action*

| Section | Experts comments and suggestion | Researchers Action |
|---|---|---|
| Content | Consider including some websites that will guide the students to specific valuable information. | Several websites were included; https://byjus.com/biology/law-independent-assortment/ https://.youtube.com/watch?v=a5GMp9BPEkA |
| Phases | In the section principles of the STEM, what does the researcher expect from engineering principles? Are these principles taught in school? *"As I understand in your model engineering serve as a context."* | Engineering serves as a context for integrating mathematics and scientific knowledge. However, the students are expected to generate ideas on genetic engineering procedures. Therefore, modified to include ideas on the procedures for genetic engineering |
| | Need to *"map out the phases and how the phases are seen to be able to engage the learners' critical thinking skills."* | Mapping of the elements and how they enhance critical thinking skills is included in chapter four. |

In summary experts' consensus shows that iSTEMim have good validity. Therefore, this instructional material could guide teachers on how to implement STEM-based instruction and provide a meaningful learning environment that could enhance critical thinking skills and achievement among secondary school students.

## 3.8 Implementation Phase

At this stage, the instructional material is implemented or put to use among the target population; senior secondary school students two (SS2). The experimental group learned using iSTEMim while the control group were taught using the traditional method that is teachers centred At this phase the students engage in iSTEMa phase in an individual and collaborative settings. The procedure for the evaluation of iSTEMim is explained in chapter four.

### 3.8.1 Pilot Testing the iSTEMim

This is the consistency with which an instrument yields the same or similar results under similar circumstances (Piaw, 2013). To determine the reliability of the iSTEMim, a Likert type questionnaire was used; strongly disagree (1), Disagree (2), Agree (3) and Strongly Agree (4). The questionnaires were developed based on guidelines from (Dick et al., 2005), experts reviewed the questionnaires. Cronbach's Alpha reliability coefficient of the questionnaire was 0.72, which was considered satisfactory (Fraenkel & Wallen, 2007). The pilot test lasted for three weeks,

The data generated from the pilot test was analysed using Cronbach's Alpha, which yielded a reliability index of 0.80 which is considered suitable. This concurs with Sekaran and Bougie (2010) who reported that a reliability value of 0.60 is adequate for instruments developed in the field of education. Similarly, Fraenkel and Wallen (2007) reported that the reliability of 80% (0.80) is considered high while below 70% (0.70) is low. Therefore, iSTEMim is considered reliable. The iSTEMim objectives, elements and phases in the completed instructional material are discussed in the next sections.

### 3.9 Learning Goal and Objectives

The instructional content of iSTEMim was selected based on the Nigerian science curriculum or syllabus. The major theme is genetics and heredity, the topics under this theme include; Mendel's first law, Mendel's second law, monohybrid and dihybrid cross, phenotypes, and genotypes, and the application of genetics. Genetic is an abstract concept that requires mental processing, but the lack of relevant instructional material to teach this abstract concept has made its learning and teaching difficult. Thus, resulting in students' unsatisfactory performance. The exploratory nature of STEM-based instruction could provide the superlative environment for the development of critical thinking skills (Jamali, Zain, Samsudin, & Ebrahim, 2017; West, 2012).

The purpose or goal of the instructional material is to enhance critical thinking skills and achievement in science among senior secondary school students through integrated STEM approach. Specifically, at the end of the use of iSTEMim students will be able to;

1. Demonstrate inference, recognition of assumption, deduction, interpretation and evaluation
2. Explain Mendel's laws, identify and explain genetic terminologies; homozygous, heterozygous, alleles, phenotype, genotype, dihybrid.
3. Use proportions, percentages and ratios to solve problems
4. Explain the concept of dominance and recessive trait

5. Identify and practice an iterative process of designing a solution through the engineering design process.
6. Integrate science and mathematics to solve the problem
7. Enhance students' motivation and learning satisfaction

The activities were aligned with the science syllabus and fit into the iSTEMim phases which are adapted from the engineering design process. This instructional material could reduce the problems students encounter in a learning environment where STEM disciplines are taught in isolation and knowledge acquired is not relevant to complex problem-solving. iSTEMa could provide the students with effective and meaningful learning where knowledge acquired can be transferred or applied in a novel situation.

### 3.10 Elements of iSTEMim

Six elements were adopted based on experts' consensus and embedded in the iSTEMa instructional materials. These elements include; the Open-ended problem, Real world scenarios, Questioning, hands-on and minds-on activities, inquiry.

These elements were adopted because they could create a learner-centred environment, engage students actively in the learning process and enhances the learner' higher cognitive processes which may lead to the development of critical thinking skills. Furthermore, they serve as themes that can integrate two or more disciplines and link problem-solving in the classroom to problem-solving in real-life, so that students see the relevance between what is learned in the classroom and their daily lives (Fortus et al., 2005).

### 3.10.1 Open-ended Problems

Rational thought does not occur in a void; there must be a bait to activate higher order thinking skills. These are problems to be solved that are presented in such a way that the problem is ill-defined and will engage students' higher mental abilities. The problem offers the opportunity to be solved from several perspectives. It is observed that an open-ended problem or ill-structured problem presents the lenses for learners to view the problem in several ways (Cox et al., 2016b). Douglas, Koro-Ljungberg, McNeill, Malcolm, and Therriault (2012) Exploring open-ended problem by learners promote their critical thinking skills. He further opined that knowledge gained during open-ended problem-solving activities (defining problem, hypothesising, selecting ideas) enhance learners problem-solving skills, critical thinking skills and ability to transfer knowledge to an unfamiliar situation. It requires the integration of STEM subject content knowledge and principles where students are anticipated to identify and determine the solution to the problem. In the process, their ability to infer, recognise assumption, deduce, interpret and evaluate could be enhanced. This suggests that the open-ended problem as an element in iSTEMim could encourage learners to engage in deduction, interpretation, evaluation, and inference. Each instructional unit is built around a problem scenario

### 3.10.2 Real World Scenario

Real-life problems imply that the problem should reflect social, personal, community and global context (Bybee, 2010; Carvalho et al., 2015). Tsupros, Kohler, and Hallinen (2009) believed that STEM education should involve a real-world problem with rigorous instructional experiences where students apply STEM disciplines that makes the connection between the classroom and the society or community. Treacy and O'Donoghue (2014) advocated that in an integrated approach to instruction, the learning content, problem or information should be presented in a scenario that is related to the students' in real life. The real-world problem may provide a meaningful context that engages the students' higher cognitive skills leading to the development of critical thinking skills. The students could be motivated to think because the problem is relevant to their daily lives. Similarly, Kim et al. (2013) accentuated in their study that real-world problem will provide an environment that will enhance critical thinking skills. Employing instructional activities based on the real-life problem could be seen as a bridge between what is happening in the classroom and the real-life (Carvalho et al., 2015; Weber, 2014).

In integrated STEM education, the student is the central figure of any instructional model, thus making the instructional process students-centred, allowing students to take responsibility for their learning. Therefore, presenting the students with a real-world problem will motivate them to learn because the instructional content was relevant to their daily life. Research has shown that students' learning characterised by real-life scenario yields positive learning effects (Treacy & O'Donoghue, 2014). Weber (2014) reported that instructional activities characterised with a real-life problem is viewed as a strategy to connect classroom instruction and real-world situation. Carvalho et al. (2015) opined that real-life problems are multidisciplinary because it has the potential to engage learners' ability to think critically (making inferences, recognising assumption, deduction, interpretation, and evaluation). This is contrary to routine problems presented in the textbooks where definite answers are found in the textbooks.

The genetic problem in this research is a real-world scenario because it is relevant to the students. The Savannah hare is familiar to the students and found in their communities. Hence, it will serve as an encouraging factor for meaningful learning which the knowledge acquired could be applied in their everyday tasks making science learning meaningful and relevant (Bodzin & Shive, 2004). Several researchers have reported that learning task connected to real life scenario produces positive outcomes (Dennis & O'Hair, 2010; Hmelo-Silver, 2004; Treacy & O'Donoghue, 2014)

In a related development, Carvalho et al. (2015) and Cox et al. (2016b) reported that one of the important approaches to enhance students' critical thinking skills (ability to infer, deduce, interpret, evaluate and recognise assumption) is to engage them in solving the real-life open-ended problem. Similarly, Douglas et al. (2012) advocated that, to promoting critical thinking skills, learners are required to explore a real-life problem.

### 3.10.3 Hands-on Activities

The instructional process becomes student-centred when learners participate actively in the learning process through physical exploration of materials, modelling, and experimentation. Tsupros et al. (2009) accentuate that solving a real-world problem using hands-on activities makes STEM subjects learning experientially. Hands-on activities in STEM-based approach should be about providing the students with the opportunity to engage in interdisciplinary learning that is beyond the boundary of the individual disciplines of science and mathematics (Johnson, 2011).

Some literature has indicated that the type learning most preferred by students are not auditory but kinaesthetic and visual which creates the opportunity for students to touch, see and interact with the instructional material and content (Brinson, 2015; Pytel, 2013; Satterthwait, 2010). Satterthwait (2010) reported that educational stakeholders understand that hands-on activities characterised by group project improve students' performance. Cruse (2012) determined the effects of hands-on activities on high school students' mathematics learning, using a quasi-experimental design and hands-on activities like mathematics games. The finding shows that students' performance was enhanced. Zeluff (2011) adopted a quantitative pre-test and post-test study to analyse hands-on and problem-based learning to determine students learning of alternative energy concepts. The findings indicated that the students who engage in hands-on activities gained 24% from pre-test to post-test scores

Consequently, engaging students in hands-on activities through the manipulation of objects (physical materials) could make the abstractness of genetic content concrete. Instructional approach characterised by hands-on activities engages students in the investigation of materials, ideas, phenomena, and understanding. Therefore, the students engage in what, why and how, of the instructional content. The process of finding answers to the what, why and how will engage learners higher order thinking skills which could enhance students' ability to think critically. Otis (2010) revealed the importance of instructional strategy characterised by hands-on activities to include; improvement of students' critical thinking and problem-solving skills, greater retention of content knowledge and creating a friendly learning environment. Hands-on learning is more applicable in science especially genetics because genetic contents are complex and abstract, thus making the abstract concept concrete

Research reports have revealed that hands-on activities make abstract science processes concrete, thereby improving students' learning experiences (Galloway & Anderson, 2014; Grumbine, 2006; Monvises et al., 2011). In this study, the students simulate how traits are inherited from parents using a coin, and to generate data to determine the probability of future generation and their percentages.

### 3.10.4 Minds-on Activities

The students' higher cognitive abilities are engaged with activities that require explanation, analysis, justification, and evaluation. These are achieved through problem-solving, questioning, open-ended problem and collaboration. When students engage actively in the learning process especially through minds-on activities such as analysis, synthesis, and evaluation, their ability to think critically is enhanced (Hirca, 2011). Literature has shown that learners active engagement in the learning process impact their ability to think critically (Pascarella, Wang, Trolian, & Blaich, 2013; Pitkäniemi & Vanninen, 2012). In this study, the students actively engage in cognitive processing such as making inferences, defining the problem, generation and selection of relevant information among others. For example during group discussion students advance and defend or justify their ideas which is a minds-on activity. Pascarella et al. (2013) opined that students' engagement in deep learning activities (activities that requires analysis, evaluation, and synthesis) yields positive effects on the ability to think critically. Ateş and Eryilmaz (2011) determine the effects of hands-on and minds-on activities on students' academic achievement in physics, the findings indicated a significant mean difference between the experimental and control group in favour of the experimental group.

The students' mental abilities are also actively engaged when learning is situated in a social context among students and between students and their facilitator(s). The learning environment should provide students with the opportunity to interact socially (Edwards, 2015; Edwards, Kemp, & Page, 2014; Nesin, 2012). Therefore, in iSTEMa, the students generate ideas individually in each phase and then meet to learners' brainstorm on the ideas they have generated individually and mutually agreed on the best idea. During brainstorming, learners engage in interpretation, explanation, justification and evaluation of their ideas. Therefore, hands-on and minds-on activities help learners to be actively engaged and are summarised as presented in Figure 3.5


*Figure 3.5.* Active engagement

### 3.10.5 Scientific inquiry

Inquiry-based activity is engaging students in science and engineering practices to gain a deeper understanding of subject content knowledge. It provides the students with the opportunity to ask questions, search for information and new ideas relevant to solve a problem. In other words, questions are formulated which are adequately answered through investigation. Students explore a solution to the problem through inquiry by employing scientific practices which are similar to the way STEM professionals solve problems in real-life.

Previous literature has reported that students critical thinking skills are enhanced when students are engaged in inquiry-based activities (Duran & Dökme, 2016; Thaiposri & Wannapiroon, 2015). In this study students engaged in asking questions, formulation of hypothesis, experimentation, gathering of data, analysis, and drawing of conclusions. These inquiry activities are mental processes that could help learners acquire skills such as; inference, deduction, interpretation, evaluation and recognising assumption. Nisa, Koestiari, Habibbulloh, and Jatmiko (2018) reported conducted a study on the effects of guided inquiry approach on students critical thinking skills among high school students in physics. The students were engaged in inquiry activities such as formulating hypothesis, induction activities and drawing of a conclusion. The results show that inquiry activities enhanced students critical thinking skills and there was a positive correlation between students' critical thinking skills and physics achievement

The emphasis on STEM education is on problem-solving which is based on the constructivist approach (Breiner, Harkness, Johnson, & Koehler, 2012). During the process of inquiry, students generate data through hands-on activities, analyse the data using mathematical skills and technology, draw a conclusion from the result of data analysis.

### 3.10.6 Questioning

This encompasses an instructional process where questions are asked to point to a direction the learning should proceed. Question prompts should guide all the activities in all the units of instruction, asking the right question by the facilitator will provide the basis for students to engage their cognitive abilities as well as employ scientific and engineering practices in the learning process. For instance, when higher order questions such as why, how, does, compare are asked, students are encouraged to give a deep explanation or justify claims which may assist them in acquiring critical thinking skills (Corley & Rauscher, 2013). Therefore, in this research the entire instructional units are driven by question prompts that are at the higher levels of Blooms Taxonomy. In support of this, literature has revealed that questioning engages students' actively, deepens understanding and enhance thinking skills (Berland et al., 2014; English & King, 2015; National Research Council, 2012).

Question prompts have been adapted to scaffold solving an open-ended problem, prompts help students to decide on a solution and justify the solution. Finding answers to question prompts that begins with; why, why not, how and what engages students critical thinking skills. It is reported that question prompts the development of critical thinking skills among learners(Ge, Planas, & Er, 2010; Jonassen, 2011; Sasson, Yehuda, & Malkinson, 2018). Sasson et al. (2018) reported that to assist students in enhancing their critical thinking skills, they should be given task requiring higher cognitive activities that will assist students in engaging in analysing, inferring, deducing and synthesising. There are also procedural questions prompts; *what do you know about the problem? Moreover, what do you need to know about the problem?* As well as *where do I get the relevant information?*

Thought provoking or effective questioning can simulate deeper learning which will enhance the learner's ability to apply the knowledge and skills, acquire in a novel situation (National Research Council, 2012) and may improve the retention span of the knowledge and skills acquired.

### 3.10.7 Teacher as Facilitator

The teacher's responsibility during the STEM integration approach to learning is to act as a facilitator during the students' group work and the entire learning process. As a facilitator, he will only respond to students by providing a fair thought-provoking question to put them on track to solving the problem. He will also provide materials where necessary and encourage all group members' participation, making sure they adhere to the rules of collaboration, help students identify the interconnections between STEM disciplines in solving problems. Cohan and Honigsfeld (2011) highlighted that students whose learning is facilitated by the teacher and they also interact with the teacher performed better in science and enhanced their higher order thinking skills. The teacher asks question prompts that will help the learners think critically.

### 3.11 Phases of iSTEMim

Guzey et al. (2016) accentuated that the engineering design process is an essential component of the new trend and vision in meaningful teaching and learning of science. Engineering is explicitly integrated into this study as highlighted in chapter 2. Five-phased engineering iterative process was adapted which is refer to as iSTEMim phases to serve as a context to integrate relevant mathematics and science concepts. The detail description of each phase of the design process is listed and explained below;

1. Engaging Problems
2. Generating Ideas /Information
3. Design Solution
4. Evaluation and Improve
5. Communicate the findings.

The details of the implementation of integrated STEM approach in the classroom is initiated by presenting the students with a genetic problem senario that is open-ended. The students will employ the iSTEMa phases as illustrated in Figure 3.6. It is important to highlight that the process is not logical but interwoven and allow the learners to move forth and back.

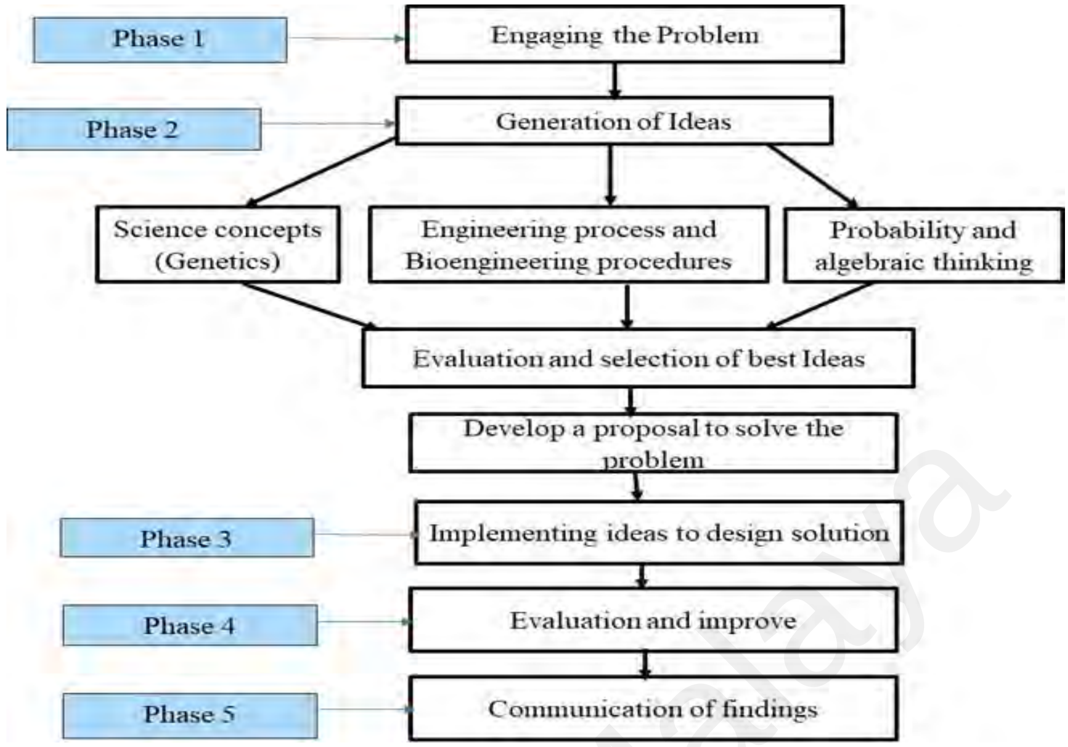


*Figure 3.6. iSTEMa Phases*

These characteristics can be implemented in both content and context model of STEM integration; however, in this study context model of STEM integration is being employed. An iterative process characterises iSTEMa; this refers to revisiting earlier completed phases to modify the process to achieve success. Technology devices were used to explore the learning content and generate ideas. However, the solution could be product (prototype) or process that will benefit society.

### 3.11.1 Engaging the Problem

This is the phase where the students seek to understand the problem, and this can be achieved through formulating a problem or defining a problem or both because both are a critical component of science and engineering practices (NRC, 2012). This phase engages the students' mind and stimulates their curiosity as well as thinking ability of the learners (Dass, 2015). Defining the problem is enhanced by asking a relevant question; *What are the components of the problem?*

Literature has advocated that the problem to be presented should be procedural and complex to arouse critical thinking and problem-solving skills (Carrio, Larramona, Banos, & Perex, 2011; Hmelo-Silver, 2004; Odom & Bell, 2011). In iSTEMim, defining the problem involve analysing or breaking down the facts of the problem into smaller segments as well as seeking to establish the cause and effects of the problem (Allen & Moll, 1986; Maloney, 2007). Defining a problem is mainly a cognitive activity which requires reflection, analysis, and deductive thinking. These cognitive activities are incorporated in this phase to scaffold learners thinking during the learning process (Dass, 2015; National Research Council, 2012; NGSS Lead States, 2013). This phase can be summarised in Figure 3.7

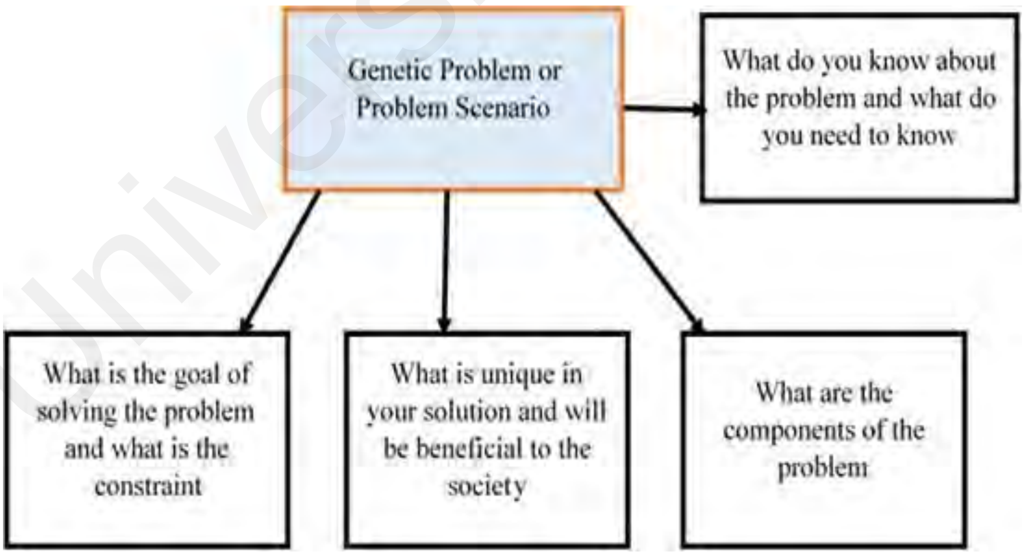


*Figure 3.7. Summary of Engaging Problem*

### 3.11.2 Generating Ideas/Information

The phase involves students actively engage in the exploration of relevant materials to generate ideas and find a solution to the problem (how a solution to the problem can be planned and solved) defined in the first phase. In this study, this phase can be achieved in some ways; first students formulate several hypotheses of the possible solution to the problem which is an important higher order thinking activity to raise different viewpoint to the problem (Odom & Bell, 2011). Based on the hypotheses, or proposed solutions, the learners will engage in gathering meaningful information from print and online materials (conduct internet search). The students research relevant STEM concepts, principles and laws that were applied in designing the solution to the problem and students may choose to consult experts.

The activities should be carefully chosen to enhance hands-on and minds-on activities, and students are allowed to explore and determine their path to the solution. The role of the teacher is to act as a facilitator of the learning process by being on hand to provide question probes that will engage the students' cognitive abilities and critical thinking skills. The students may choose to consult an expert to gather information. After this, students will brainstorm, formulate ideas, discuss strategies and collaborate to select the best idea to design a solution. It was earlier observed that collaboration to generate ideas enhances students' critical thinking skill acquisition and achievement in an engineering-based problem-solving (English et al., 2013). This phase is illustrated in Figure 3.8

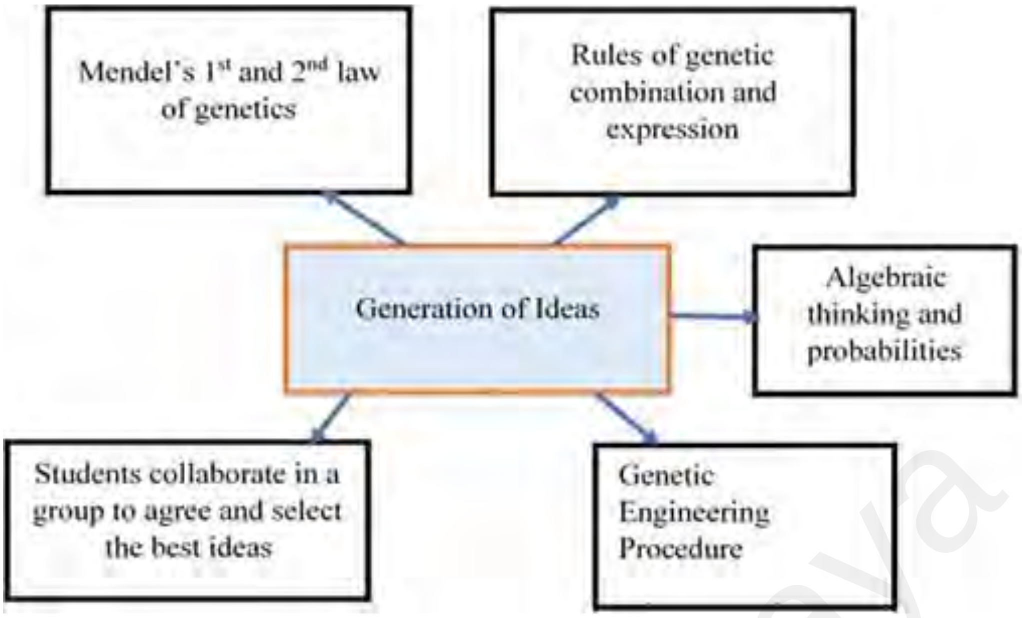


*Figure 3.8. Summary of Generation of Ideas*

### 3.11.3 Designing the Solution

In this phase, the ideas generated (scientific, mathematical laws, concepts, and principles), data collected, analysed and interpreted to reveal the relationship among constructs and form the basis for making explanation by the students in the previous phase are applied to design and drawing a conclusion. This involves making diagrams, sketching designs for the initial model which is an essential aspect of the engineering design process. This design, sketching is in the form of representation of students' ideas which was transformed into a 2D or 3D model; this demonstrates how the students can integrate concepts and principles among the STEM disciplines. The design should reflect evidence such as patterns, measurement to support the sketch and a solution to the problem, demonstrate a significant relationship, pattern, and features among variables that can best solve the problem. This phase can be illustrated in Figure 3.9

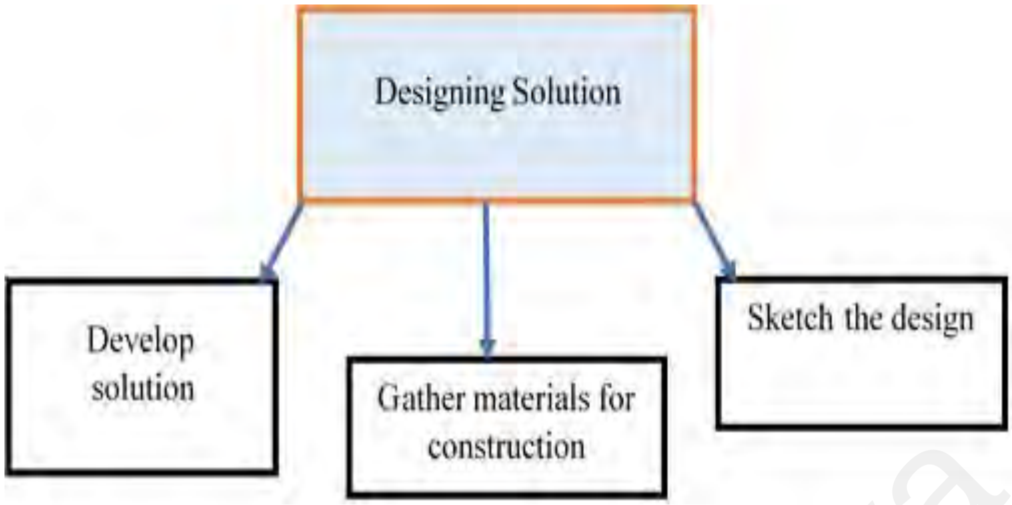


*Figure 3.9. Designing Solution*

### 3.11.4 Evaluation

At this stage, the students evaluate their design process and prototype based on the specification or goal of solving the problem. During the evaluation, students test the artefact or model, assess whether the goal of the exercise has been achieved as well as check the constraint. During the evaluation the students reflect on the entire learning or design process; consequently, students may need to redesign if the goal is not met or achieved. During the evaluation in this study, students will seek to answer the following questions; *does this design solution meets the requirements of the clients?* If the answer is yes, *why?* And if no, *why not?* Suggest ways to improve the design. This phase is illustrated in Figure 3.10

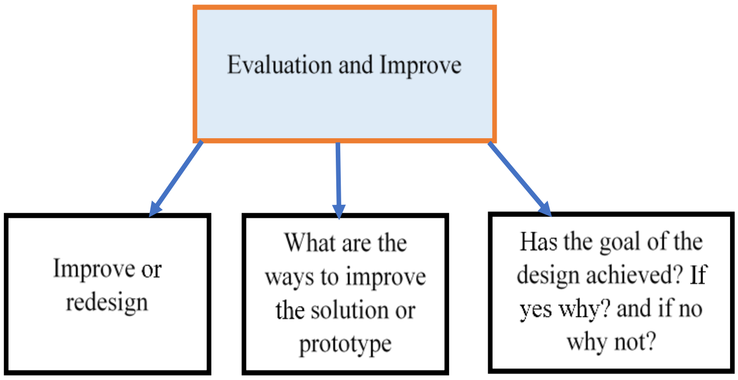


*Figure 3.10. Evaluation of the process*

It is reported that if the evaluation is carefully done and implemented, it can enhance the achievement of learning objectives (Pellegrino, 2014) because it allows the learner to reflect on the entire learning process.

### 3.11.5 Communication of Ideas

Students present and share their discoveries, ideas and finding to others in all the phases, the communication of ideas and the outcome of a design is an essential aspect of the engineering process. Therefore, students record the step by step of the design process and communicate same to others and to their clients which will include; ideas generated about important science and mathematics concepts, the design requirement, constraint and clear illustration of the prototype.

In this study, students communicate their GMO or finding to the class through multiple representations such as text, diagrams, graphics, and prototype. The students will explain the genetic engineering process of the Genetic Modified Organism (GMO) highlighting its economic value to the society and the problem the GMO will solve as well as the name of the GMO. In this phase, the students will also be involved in the presentation of arguments to support or oppose the use of genetically modified organisms which is a social-science issue. Literature has established that scientific argumentation enhances students' thinking abilities and conceptual understanding (Acar, Patton, & White, 2015; Foong & Daniel, 2013; Kuhn, 2010). Hence, in this study, students will engage in defending their views from evidence as well as present and defend their ideas on the social scientific issue of GMO.

The summary of the phases, sub-phases and the description of each phase is highlighted in Table 3.8

*Table 3.8*

*Summary of the instructional Phases of iSTEMa*

| iSTEMa Phases | Sub-phases | Task/Description |
|---|---|---|
| Engaging Problem | Understanding and defining the Problem | - Analysing the problem by breaking down the problem into smaller segments (Maloney, 2007),<br>- Establish the cause and effects of the problem<br>- Establish why the problem<br>- Establishing the goal and constraint of the problem |
| Generating Ideas /Information | exploration and planning | - Formulation of the possible and alternative ways to solve the problem (Bernik & Žnidaršič, 2012)<br>- Gathering meaningful information from print and online materials, consulting experts,<br>- Generate scientific and mathematical concepts and principles that will be applied<br>- Develop a plan and established a strategy |
| Design Solution | Sketch and interpret Design<br>Convert design to a prototype | - Application of mathematics and science concepts to the design<br>- Sketches to illustrate the design<br>- Translate the sketches into a 2D or 3D based on the goal of the problem the problem<br>- Interpret the design |
| Evaluation | Evaluate the design process and goal of the engineering process | - Students evaluate their design process and prototype based on the specification or goal of the design challenge<br>- Learners' reflect on the entire process. |
| Communicating Findings | Share and defend ideas, discoveries, and argumentation | - Students share, their discoveries, ideas and finding to others and their clients in all the phases<br>- This is achieved through graphic, text, diagrams and a 3D.<br>- Students are involved in argumentation |

## 3.12 The Outlook of the Prepared iSTEMim

The outlook of the completed iSTEMa instructional material is made up of a cover page, table of contents, goal or purpose, and objectives, among others. The cover page of iSTEMim is as presented in Figure3.11


UNIVERSITI MALAYA
KUALA LUMPUR

INTEGRATED SCIENCE, TECHNOLOGY, ENGINEERING AND MATHEMATICS APPROACH (iSTEMa)

INSTRUCTIONAL MATERIAL FOR SENIOR SECONDARY SCHOOL

2018

*Figure 3.11. Cover Page*

The cover page is made up of the University of Malaya logo since the work is in fulfilment of the award of PhD in science education from the institution. The cover page has the title of the instructional material and the target population.

The contents of the iSTEMim are highlighted in the table of contents which is made of sections and subsections and their pages for easy navigation of the users. The table of content is one of the essential elements of a completed module (Hashim, 1999). The table of content is as presented in Figure 3.12

Table of Contents



*Figure 3.12. Table of Content*

The goal and objectives are essential components of a module or instructional material because the module is designed to achieve a specified goal and objectives. In this study, the goal and performance objectives were clearly stated as presented in Figure 3.13

**Background**

iSTEMa is an instructional material that provide guide on the integration of engineering as a context to learn science and mathematics using engineering design process to solve real-world open-ended problem. In the process students' critical thinking skills and achievement in science is enhanced. In this study, engineering is explicitly integrated and not an add on.

**Purpose and Objectives**

The purpose or goal of the instructional material is to enhance critical thinking skills and achievement in science among secondary school students through integrated STEM approach. Specifically, At the end of the use of the iSTEMa instructional material students will be able to;

1. Enhance their critical thinking skills (inference, recognizing assumption, deduction, interpretation and evaluation)
2. Enhance students' achievement in genetics (explain Mendel's laws, genetic probability and terminology
3. Identify and practice an iterative process of designing solution or a prototype through the engineering design process
4. Identify the relevance of STEM to their daily lives
5. Use technology as an instructional resource and engage in collaboration
6. Enhance motivation and learning satisfaction

*Figure 3.13. Purpose and Objectives*

### 3.12.1 Iterative Process

Although the description of the activities in each phase may give the impression that the phases are chronological and autonomous from one another, the actual implementation could involve individuals revisiting previous phases in the learning process. The phases adopted were identified and established from the literature reviewed and were based on research question one as reported in chapter one. The phases adopted, and other elements were sent to experts. The feedback was collected and harvested based on the experts' consensus. The final elements were sent back to the experts for their final consensus. During the planning, the researcher moves forth and back to align the instructional task with the phases and the activities. For example, based on the generation of ideas the objectives of the task were adjusted, and the materials for the group projects were reviewed severally and were locally sourced. Students work individually to generate ideas in each phase and then meet in a group to brainstorm. The iSTEMim iterative process is as presented in Figure 3.14

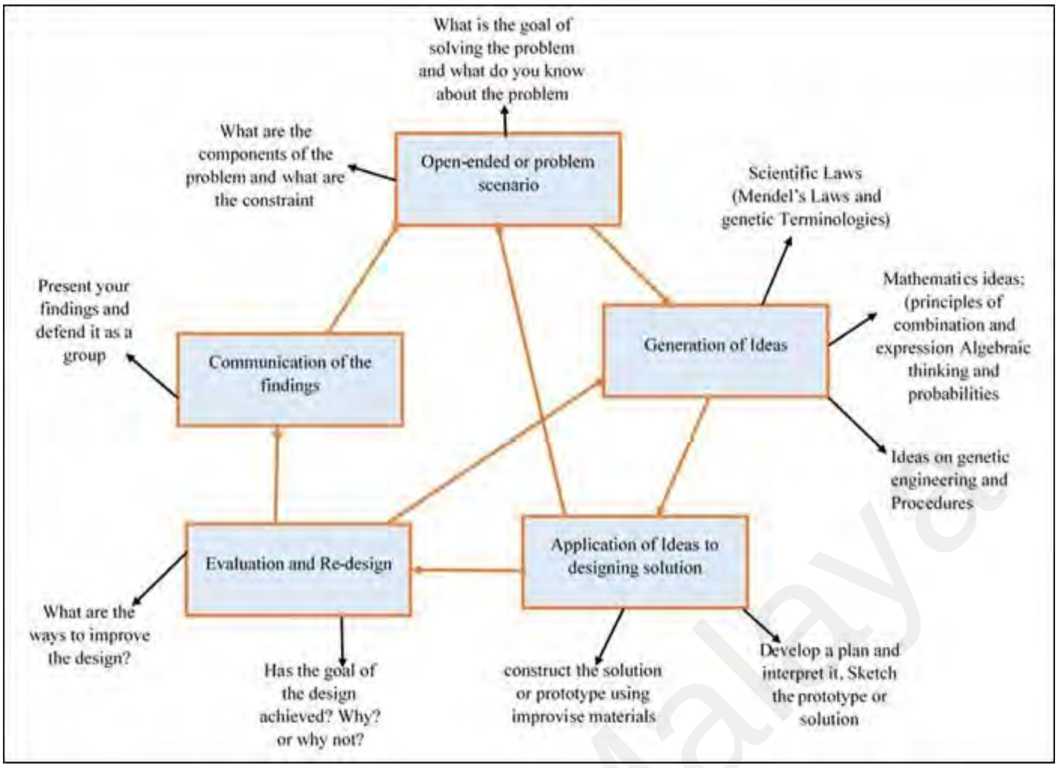


*Figure 3.14. iSTEMim Iterative Process*

The iterative process of iSTEMim could improve the students' critical thinking skills because it allows students to reflect on what is already done in the previous phases, thus constantly reflecting on previous ideas. This could help learners raise relevant questions, think out of the box and actively engage in the entire learning process and become responsible for their learning. The iterative process could engage students' higher order thinking abilities which could lead to the development of critical thinking skills. Billiar, Hubelbank, Oliva, and Camesano (2014)reported that engineering design process is phases of an instructional path that demonstrates a constant process of reflection on previous phases which will help learners ask relevant questions and engage in minds-on activities. The engineering design process differs from the scientific inquiry process because it is cyclic and not linear, cycle help learners identify and select an excellent solution to a problem to achieve a goal. The generation of ideas or solution necessitates iteration (Billiar et al., 2014). One of the most critical phases is defining the problem phase at this phase the students establish the goal, requirement, and constraints of solving the problem and will continuously refer to it in other phases. For instance, in solving a problem through design, one may discover at any phase of the process the need to revisit the previous phase or phases. Example during generating ideas one discovers vital information or component of the problem that was not addressed in the engaging problem phase and will have to revisit that phase to address it. The ideas chosen for the solution may not be workable for obvious reasons and may necessitate redefining the problem and generating more information and ideas.

It was observed by Petroski (2010) that the engineering design process has many phases where halts are essential, and learners move forth and back to achieve the goal of the design task. In this study, the iterative cycle begins with engaging the problem, and the last phase is the communication of findings. The iterative nature of engineering could stimulate deductive and abductive reasoning; generation of several likely solutions to the problem which could enhance critical thinking skills (Jøsang, 2008). The iterative nature of the iSTEMim and the task embedded provided the opportunity for students to think critically as they engage in the entire learning process.

### 3.12.2 Mapping of iSTEMa Phases, Elements, and Critical thinking Skills

Elements of critical thinking skills were embedded in iSTEMa phases which could have enhanced critical thinking skills. The researcher provided an overview on how the iSTEMa elements were linked to a specific suskill of critical thinking skills. It was established from the analysis that different elements supported different and several cognitive processes. The mapping was done based on the data from interviews and observation. From the qualitative analysis of data, the findings clearly show certain elements are linked or associated with specific learning subtheme or category. Example students' engagement to define the open-ended problem help them to reason from general scenario to a specific goal of the problem which is deductive activity. Students also interpret how their unique animal will look like which is interpretation. In a nutshell, during the mapping, it can be inferred that different iSTEMa elements support different learning category or dimension. Therefore, the mapping was done to establish which element help to enhance which learning dimension of critical thinking. The mapping is highlighted as presented in Table 3.9

Table 3.9

*Mapping iSTEMa Phases, Elements, and Critical Thinking Skills*

| iSTEMa Phases | iSTEMa/ Critical Thinking Elements | Description | Critical Thinking Skills |
|---|---|---|---|
| Engaging Problem | Open-ended Problem<br>Real-world problem<br>Questioning | What do you know about the problem?<br>Analyse the problem to its component | Recognising assumption |
| | | Highlight the goal of the problem | Deduction<br>Interpretation |
| Generation of Ideas | Minds-on activity<br>Hands-on<br>Inquiry<br>Questioning | Generate ideas online and textbooks, experimentation, manipulation of materials, presentation, explanation, and justification of ideas | Interpretation also, recognising Assumptions |
| | Collaboration | Collaboration to select the best idea | Evaluation, and Inference |
| Designing Solution | Hands and Minds-on Activities | Designing and constructing a solution | Evaluation |
| Evaluation | Minds-on Activity<br>Questioning | Assessing the solution or artefacts example; is the goal of solving the problem achieved? Why or why not? | Evaluation<br>Inference |
| Communication of Findings | Inquiry and Minds-on Activity | Communicating the findings | Interpretation |

Table 3.9 indicates the iSTEMa phases, elements, a brief description of students' engagement in each phase and the critical thinking skill that could be enhanced in each phase. It was observed that that apart from the five subskills of inference, recognising assumption, deduction, interpretation, and evaluation that are measured in this study, other skills could also be enhanced. For example, in the first phase students are expected to reflect on their previous knowledge to identify what they know about the problem, that is, to activate their prior knowledge thus engaging in reflective reasoning; critical thinking process that deals with making judgement about what has happened (Khalid, Ahmad, Karim, Daud, & Din, 2015). The students could also acquire communication skills as they articulate their findings and communicating it; during this phase, the students also reflect in all they have done in all the phases. The students work individually in each phase and meet at the end of each phase to brainstorm.

## 3.13 Overview of the iSTEMim

Cox et al. (2016b) highlighted that skills like critical thinking, problem-solving and collaboration could be influenced in biology instruction if students are guided to solve problems using engineering design. This can be achieved through modelling processes in biology, similar to what engineers do in real-life problem-solving using engineering design. The primary focus of the instructional material was the application of genetic knowledge (dominance, recessive, phenotype, genotype among others) to design an imaginary genetic modified rabbit. In this instructional material, engineering is integrated as the engineering design process. The students will write a proposal highlighting the benefit of the genetically modified organism to society. The students represented their idea in a sketch of their Genetically Modified Organism (GMO). The students will assemble local materials to construct their genetically modified rabbit, evaluate their prototype based on the goal of solving the problem. The students finally communicated their results and findings to their classmates who serve as the client. During the activities, mathematics was employed as algebraic thinking where students established the general rule of how traits are transferred from parents to offspring. During construction of the organism, students quantify the materials. The use of the computer to search for relevant information and perform simple statistics such as bar chart and line graph.

### 3.13.1 Task using iSTEMa

The learning process using iSTEMa was made of three tasks which lasted for six (6) weeks intervention. Three (3) lessons a week; one single lesson of forty minutes and a double lesson of eighty (80) minutes. The tasks include;

Task 1: The case of the Savanna Hare
Task 2: Modelling Mendelian Genetics
Task 3: Black + Black = White.
Task 4: Paternity disputes
An example of how the students performed task one is attached as Appendix 10

### 3.13.2 iSTEMim Worksheet

Teaching and learning materials are very vital in enhancing effective learning (Romli, Abdurrahman, & Riyadi, 2018). The worksheet is one of the learning materials that are in print (printed material) that is designed and used to enhance students' thinking and a deeper understanding of instructional content. It provides the opportunity for learning by doing. The worksheet is seen as a learning instrument with steps and activities for the students to learn (Yildirim, Kurt, & Ayas, 2011). It provides support for learners' active engagement in the learning process and enhances effective instructional process (Kaymakcı, 2012). The use of Worksheet is more appropriate when students are expected to solve an open-ended or ill-structured problem in the classroom. Yildirim et al. (2011) investigated the effects of worksheets on students' achievement on the factors affecting equilibrium. Quantitatively and qualitatively data was collected. The finding shows that the experimental group (students that learn using worksheet) perform better than the comparative group. Romli et al. (2018) in their study, reported that worksheets design with an open-ended question would motivate students to find a solution to the questions and in the process develop their thinking skills. In their study, they found that instructional materials like open-ended worksheets enhance students thinking skills and improves students' performance in scientific concepts.

In view of the preceding, the designed iSTEMim worksheet in this study was for students' classroom learning experiences. The iSTEMim worksheet was designed by the researcher to solve an open-ended problem. The worksheet was made up of an introduction and iSTEMim phases; engaging the problem, generate ideas, design solution, evaluate and improve and communicate findings. The worksheet contains questions, open-ended scenario, pictures, and exercise questions. Each student is given a worksheet each, and the student is expected to answer the question, and fill in his ideas in each phase. The student then meets in a group to brainstorm their ideas.

## 3.14 Summary

This chapter discussed the learning theories that supported this study; Vygotsky social constructivist theory. The iSTEMa approach was contextualised to provide a clear understanding of the nature of classroom instruction. Data was collected and analysed to provide an answer to the research question which states that; what are the elements of iSTEMa instructional materials that could enhance critical thinking skills and genetic achievement? The ADDIE was adopted for the preparation of the iSTEMa instructional material. Quantitative data was collected through questionnaire while qualitative data were collected through open-ended question and interviews to validate the components and elements of the iSTEMa. The data were analysed and based on the findings from questionnaires and experts' comments and observation the elements of iSTEMa were established. The results of the validation of the practicability or usability form experts and students indicated that the instructional material was satisfactory and useable.

# CHAPTER 4

# METHODOLOGY

## 4.1 Introduction

The study determined the effects of iSTEMa on senior secondary school students' critical thinking skills and achievement in genetics. This chapter discussed the following: research design, the population, sample and sampling technique, instruments for data collection, validation and reliability of the instruments, data collection and data analysis.

## 4.2 Research Design

A concurrent mixed method design was adopted for this study. It is the deliberate collection of data using quantitative and qualitative methods and using the combined strength of the two to achieve the objectives of the research study (Johnson & Christensen, 2012; Klassen, Creswell, Clark, Smith, & Meissner, 2012). The quantitative data collected was used to measure the relative effects of iSTEMa, while the qualitative data was used to understand students' experiences of learning using iSTEMim (integrated STEM instructional material) and evidence of how critical thinking skills was acquired. Therefore, the formulated hypotheses can be verified deductively, while emergent pattern from students' learning experiences with iSTEMa can be inductively established (Creswell, 2009).

The researcher used parallel data handling where the data collected and analysed independently and mix during the interpretation or discussion of results. The concurrent mixed method is as presented in Figure 4.1

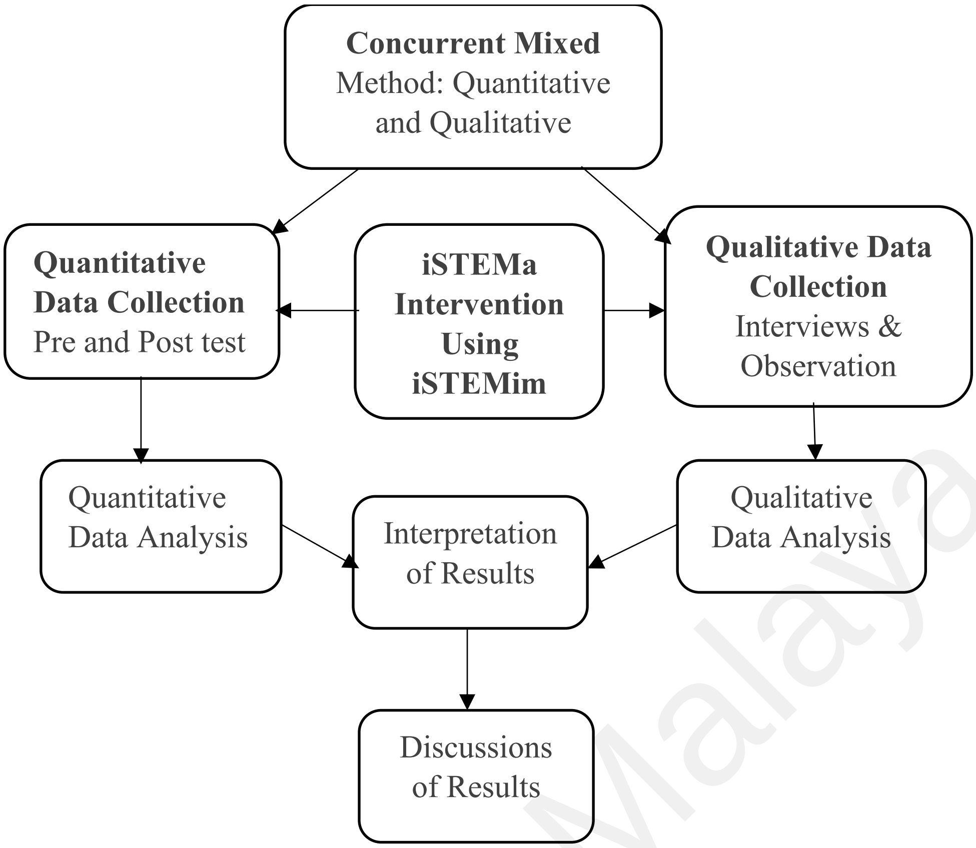


*Figure 4.1. Concurrent Mixed Method Adapted from Creswell and Clark (2011)*

## 4.3 Quantitative Research Component

This segment discusses the quantitative design method, samples and sampling, instruments, and data collection procedures. The focus of the quantitative component was to test the formulated hypotheses as highlighted in chapter 1

### 4.3.1 Factorial Design

The design allowed the researcher to examine two or more independent variables or factors and each independent variable is examined on 2 or more levels (Cresswell, 2012). Therefore, the factorial design was adopted, the independent variables are the types of instructional approaches (iSTEMa and traditional) while the levels or factor two is students' academic abilities (high and low). This is as illustrated in Figure 4.2.

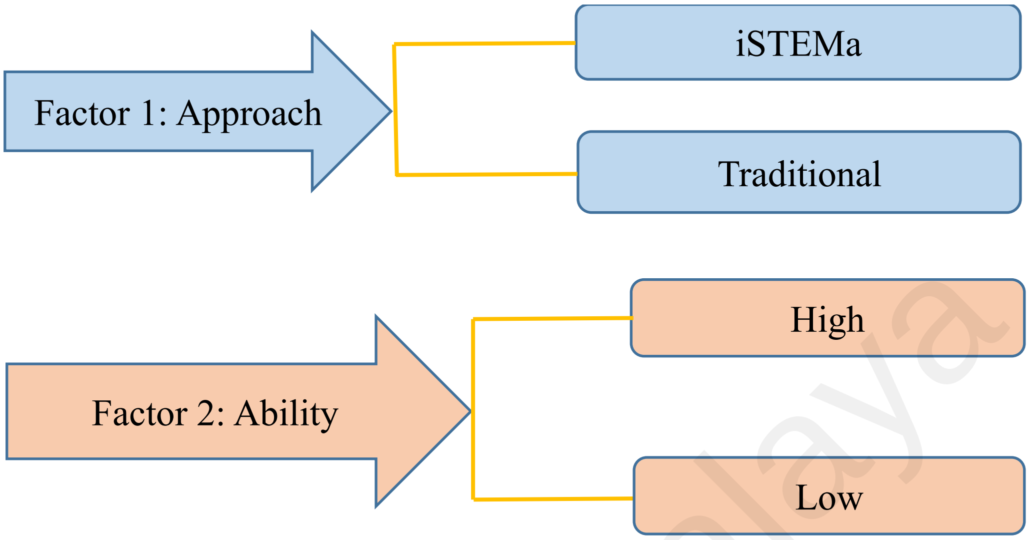


*Figure 4.2.* 2x2 Factorial Design

The design can further be represented in a tabular form to show how the factorial design levels or groups were assigned to the two independent variables in this study as presented in Table 4.1.

Table 4.1

*Factorial Levels of the Independent Variables*

| **Group** | **Academic Ability** | **Instructional Approach** | **Dependent Variable** |
|---|---|---|---|
| 1 | High | iSTEMa | Post-test (critical thinking score and genetic achievement score) |
| 2 | Low | iSTEMa | Post-test (critical thinking score and genetic achievement score) |
| 3 | High | Traditional | Post-test (critical thinking score and genetic achievement score) |
| 4 | Low | Traditional | Post-test (critical thinking score and genetic achievement score) |

Given the preceding, the factorial design adopted for this study was "2 x 2" indicating two independent variables a two levels of students' academic ability (high and low), which gives a total of four groups. Consequently, in this factorial design, two groups high, and low was treated with iSTEMa while the other two high and low was taught with the traditional teaching method. The study used two classes, in each class, there were two groups high, and low for the iSTEMa and traditional.

#### 4.3.2 Duration of the Study

The duration of this research study was eight (8) weeks, including activities such as familiarisation visit, pre-test administration, treatment and post-test, and interviews

1. Pre-test of critical thinking test and Genetic Achievement Test (GAT) was administered in the first week before the research treatment or intervention.
2. The iSTEMa was the intervention for the experimental group while the traditional method of teaching was used for the control group. During the intervention, the students in the iSTEMa group were exposed to the iSTEMim. While students used the iSTEMim classroom observations were done.
3. After the intervention, critical thinking test and GAT was administered as post-test and interviews conducted

#### 4.3.3 Research Variables

The research study has the following variables. The independent variable is the instructional strategies or approaches; these are variables that can be manipulated to see its influence on the dependent variables (Creswell, 2009). The independent variable is made up of iSTEMa, and the traditional method. The iSTEMa is characterised by student-centred activities employing the five phases of the iSTEMa learning process while the traditional method is teacher-centred activities.

In this study, the dependent variables are the Critical thinking score and students' achievement score in genetics. The tests instrument (critical thinking and genetic achievement) were administered before the treatment as a pre-test and after the treatment as post-test for both the two groups. In this study student ability is the moderating variables (Creswell, 2009). The independent and dependent variable are illustrated as presented in Figure 4.3

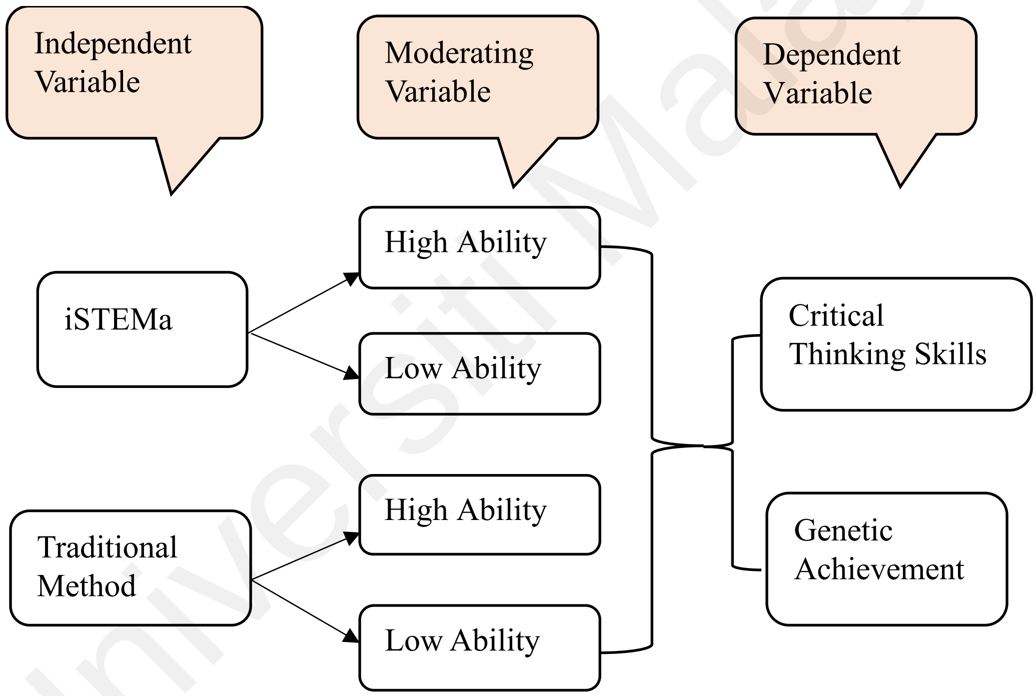


*Figure 4.3.* Independent, Moderating and Dependent Variable

## 4.4 Population

The population of this study was all senior secondary classes two (SSII), federal government colleges in Minna, Niger State of Nigeria. This population has been taught biology in their senior secondary class one (SSI). During their SSI, they have been taught the pre-requisites concepts to learn genetics such as the cell theory and cell division which include mitosis and meiosis.

### 4.4.1 Research Sampling Technique and Sample

Sampling technique adopted is probability sampling which is associated with quantitative design. Because generalising the result to the population from the statistical result and findings is the primary focus of the study. The researcher will seek to adopt a multi-stage sampling technique. First, convenient sampling technique was adopted to select two schools, A and B, from the population. These schools were sampled on the ground that the schools were from urban areas; the schools were a public school and mixed gender (male and female). The schools both have functional computer laboratories with internet facilities and a functional biology laboratory. The pattern of students' admission and recruitment of teachers are the same and manage by the Federal Ministry of Education (FME). School A was randomly selected as the experimental (iSTEMa) group and school B as control (traditional) group (Cresswell, 2012).

#### a Research Sample

This refers to the number of subjects (students) selected from a population for a research study (Piaw, 2012). The research sample is also seen as a subset or a unit where information is obtained. There were three classes of science students with an average of fifty students per class. Seventeen students were randomly selected per class, were randomly selected for the intervention in school A as experimental (iSTEMa) group. Therefore, the experimental group was made up of Fifty-one (51);

male 28, and female 23. On the other hand, forty-nine (49); male 29, and female 20 randomly selected as the control (traditional) group in school B.

The average score of the students' achievement in science in one academic year in senior secondary II (SSII) was used to group the students into high and low ability. Slavin (1993) reported that students' ability could be classified based on several factors or combination of factors; intelligent quotient, academic achievement, and teacher judgement. As reviewed in chapter two, Texas Education Agency (TEA) classified their test into $< {}^{31}/_{50}$ or $<60\%$ as low achievers, ${}^{31\text{-}44}/_{50}$ or 62-88% medium achievers, while performance of $\geq 45$ or 90% and above as high achievers (Han, Capraro, & Capraro, 2015; Texas Education Agency, 2009). Given the preceding, using students' average prior science achievement in the previous year, this current study adopted $\geq 60\%$ as high achievers, and $\leq 59\%$ as low achievers. The distribution of students is as presented in Table 4.2

Table 4.2

*Distribution of Participants based on Ability*

| **Group** | **Ability Levels** | | **Total** |
|---|---|---|---|
| | High | Low | |
| iSTEMa | 20 | 31 | 51 |
| Traditional | 19 | 30 | 49 |

Table 4.2 shows the distribution of the sample size of the iSTEMa and traditional group. The iSTEMa group (n=51), had 20 (39.22%), high achievers, while the number of low achievers was 31 (60.78). In the iSTEMa group, the number of male participants was 28 (54.90%) and female 23 (45.10%). On the other hand, in the

traditional group, the number of high achievers were 19 (39.78%) while low achievers amounted to 30 (61.22%). In the traditional group, the number of male participants was 29 (59.18%) and female 20 (40.82%).

## 4.5 Research Instruments

This section deals with quantitative instruments for data collection in this research study. The research instruments are Critical Thinking Skill Test (Appendix 1) and Genetic Achievement Test (GAT) attached as Appendix 2. The Critical Thinking Test and GAT were used to collect data before and after the intervention as the pre-test and post-test respectively.

### 4.5.1 Critical Thinking Skill Test

Critical thinking is an essential construct in this research study. One of the objectives of this study was to scaffold the acquisition of critical thinking skills among secondary school students. Given the literature reviewed on critical thinking, it was reported that there is no universally accepted theory and assessment test of thinking skills (Piaw, 2010; Starko, 2004; Tiruneh et al., 2017). Starko (2004) argues that the use of a thinking test instrument is determined by the objective and purpose of the instrument. The criteria for the development of a thinking instrument must include a) be based on a thinking theory; b) relevant to critical thinking behaviour in real life; c) yield score or data that will be reliable. It also includes; d) the instrument should include testing instructions (duration and scoring procedures); and e) it should be constructed to motivate the learner or individual to respond with regards to the individual's experience (Paul, 2004; Watson & Glaser, 1980).

Several studies were reviewed on instruments measuring critical thinking skills (Allen & Moll, 1986; Alrubai, 2014; Jungwirth & Dreyfus, 1990; Watson & Glaser, 1980). Most popular thinking tests available such as Watson-Glaser Critical Thinking Appraisal and Cornell Critical Thinking Test which is generic. Consequently, the need to prepare a critical test to measure critical thinking skills related to science and school phenomena.

The critical thinking instrument constructed in this study was based on Watson-Glaser Critical Thinking Appraisal ideas and definition of critical thinking as well as their sub-skills. Critical thinking is a composite of knowledge, attitudes, and skills. Watson and Glaser classified critical thinking into six subskills which are an inference, recognition of assumption, deduction, interpretation, and evaluation of arguments (Watson & Glaser, 1991). The objective (multiple choice) scoring format of WGCTA was also adopted, based on the justification that the reliability of the test instrument can be enhanced. Table 4.3 shows the list of subskills, the number of items in each subskill and the options of the answers for each item.

Table 4.3

*Critical Thinking Test Distribution*

| Sub-Skill | Items | Option in Each item |
|---|---|---|
| Recognition of assumption | 8 | 2 Option: Yes (for assumption made)<br>No (for assumption not made) |
| Inference | 8 | 5 Options: True (T), Probably True (PT), Insufficient Data (ID), Probably False (PF) False (F) |
| Deduction | 8 | 2 Option: Yes (Conclusion Follows)<br>No (Conclusion does not follow) |
| Interpretation | 8 | 2 Option Yes (Conclusion follows) No (conclusion does not follow) |
| Evaluation of Arguments | 8 | 2 Option STRONG Arguments or WEAK Arguments |
| Total | 40 | |

Table 4.3 shows forty (40) items for each subskill of critical thinking. The items were adapted and modified from other tests for this present research study. For example, the short version of WGCTA had 40 items to be administered in 45 minutes (Bernard et al., 2008). Therefore, this study produced 40 test items in line with the WGTA short form. Appendix 1 shows the complete version of the Critical Thinking Test. For example, items 5,6,7,8, in the subskill of inference were adopted from Allen and Moll (1986) and items 17,18,19,20 and 21 in deduction subskill were adopted from Jungwirth and Dreyfus (1990)

An example of an adopted and modified question from inference sub-skill is as presented in Table 4.4.

Table 4.4

*Sample of original and modified critical thinking question*

| **Original question** | **Modified Question** |
|---|---|
| "A student placed a white female guinea pig with three male guinea pigs (one white two blacks) later the female | A farmer placed a female red rabbit in pen with three male rabbits (two white |

| | |
|---|---|
| gave birth to a white offspring. Which of the following is the best choice concerning the father of the offspring?<br>1) The white male must be the father<br>2) Either of the black males must be the father<br>3) The white male could be the father<br>4) Either of the black males could be the father<br>5) Option 3 and 4 are the best choice" (Allen &Moll, 1986) | and one red). After sometimes the female gave birth to one red offspring.<br>1. The red male rabbit is the father<br>2. One of the white male rabbits must be the father<br>3. One of the two white male rabbits could be the father<br>4. The offspring is a female |

The modified question used a rabbit that the students are familiar and culturally accepted; they are accepted by all members of the communities irrespective of religion or creed. Rabbits were also considered as friendly animals. Four options appear suitable because of the last option in the original looks like repetition. The ability to draw an early conclusion from observed facts or given statement, opinion or problem. In inference, a statement is made which should be seen as a fact. From the statement, conclusions were drawn; therefore, the students were expected to examine the statement and decide on the degree of being true or false. For each inference, there were options on their answer sheet from which they would choose.

### 4.5.2 Validation of Critical Thinking Test

Validation of an instrument refers to the ability of the instrument to accurately measure what is intended to measure or how good the test measure what it is supposed to measure, therefore, the validation of the critical test instrument. The critical thinking test was validated based on the face and content validity as well as internal consistency validity.

a Content Validity:

The researcher solicited and employed 2 experts in psychometric testing from the National Examination Council (NECO) of Nigeria, 2 biologe education esperts with more than 10 years' experience biology teacher in a government secondary school in Niger state. 3 science education experts from the Department of Science Education, Federal University of Technology Minna and 1 expert from University Kebangsaan Malaysia (UKM) (Polit & Beck, 2006). These experts checked for content validity and agreed on 75% of the test items were relevant, and modification was recommended in the remaining 25% or 10 questions; recognition of assumption 12, 13 and 14; deduction subskill item 22, 23 and 24; evaluation item 33, 34, 35 and 36 The test items were modified based on psychometric and science education experts' observation, comments, and feedback. An example of a modified question in the subskill of interpretation. The original question was;

*Mr Jeff conducted a study on the relationship between students age and the creative ability, and the following data were obtained. Interpret the data in the Table below.*

| Years | Creative increase rate |
|---|---|
| 5 years | 5 |
| 10 years | 7 |
| 15 years | 10 |
| 20 years | 15 |
| 30 years | 12 |
| 40 years | 10 |
| 50 years | 8 |

Based on the experts' comments (this question should be reconstructed or modified to be science-based critical thinking question). The question was modified as follows;

**Statement;** Prosper is a biology teacher who demonstrated the relationship between the rate of plant growth and light intensity (inherited trait and the environment). In his investigation he obtained the following data;

| Intensity of Light | Plants growth rate (inches) | |
|---|---|---|
| 200 | 5 | |
| 400 | 7 | |
| 800 | 9 | |
| 1000 | 10 | |
| 1500 | 13 | |
| 2000 | 15 | |
| 2200 | 13.5 | |
| 2600 | 9 | |
| 3000 | 7 | |

29. As the growth of plants increases, light intensity increases and then decrease
30. Light intensity increases plant growth increases steadily.
31. As the intensity of light increases, the growth of plant increases and then decreases
32. There is no relationship between light intensity and plant growth

b Internal Consistency Validity

The internal consistency was determined using the split-half method. The test was administered to a sample of 50 students for the pilot test, the sample was part of the population, but was not selected for the actual study, the data obtained was used to calculate for the internal consistency validity of the test instrument. Using SPSS (Pearson Product Moment Correlation), the reliability coefficient was calculated based on the subskill of inference, recognition of assumption, deduction, interpretation, and evaluation of arguments. The test lasted for sixty (60) minutes. One mark was allocated to each correct item and a total maximum score of 40 marks

The results yielded a correlation coefficient of between 0.70 and 0.75. This is in agreement with (Tucker, 2007) who reported that a reliability coefficient of 0.50 - 0.80 is considered moderate while above 0.80 is considered high. Therefore, the reliability coefficient obtained for this instrument is considered acceptable and appropriate for this research.

### 4.5.3 Threats to Research Validity

Several factors could influence the outcome of experimental research other than the research intervention. These potential threats were identified, and the research was designed to minimise these potential threats. There are two types of threats that can influence the validity of the results or outcome of research; internal validity threats and external validity threads (Creswell, 2014).

#### a Threats to Internal Validity

Factors such as experimental treatment, procedures and practices of the participants that could influence the inference of the findings on the population (Creswell, 2014; Tuckman, 1999). In this study, the potential threats, description and the action taken to overcome or minimise the threats as presented in Table 4.5.

*Table 4.5*

Threats to Internal Validity and Action Taken

| **Threats** | **Description** | **Action by Researcher** |
|---|---|---|
| History | As a result of the research duration, certain events may interfere which may impact the outcome other than the treatment | Both the iSTEMa and traditional group engaged in similar daily activities; both are unity schools and are boarding. No unanticipated event took place |
| Maturation | The sample selected could mature or change by getting older during the experiment, and that could influence the results | The participants were about the same age, thus their changes if any may be similar and may not impact the result significantly |
| Testing | Students become familiar with the post-test items because they participated in the pre-test and that could affect the result | The test items in the pre-test were reshuffled. The time between the pre-test and post-test was seven weeks |
| Selection | Selecting participants with distinct characteristics which may give one group advantage over another which may influence the outcome | The researcher adopted random sampling to select the iSTEMa and traditional group as well as select the participants in each group |
| Mortality | This is the case were participants died or dropped out of the experiment, and that may impact the outcome of the research. | The researcher recruited a large number of sample for this study. The sample size was one hundred (100), students |
| Instrumentation | Change in the instrument between pre-test and post-test may affect the outcome of the research | The researcher used the same instrument for both pre-test and post-test for both the critical thinking and achievement |
| Contamination or Diffusion of Treatment | The experimental and control group may share ideas about the treatment. This exchange of ideas may influence the results of both groups | The researcher keeps the iSTEMa, and traditional group separate from each other and both schools were boarding schools and located far apart the chances of them meeting was not likely |

### b Threats to External Validity

External validity threats occur when researchers draw inferences from the sample of the study to other population, past or future circumstances or situation and other settings. The threats to external validity may arise because of the sample unique features, setting and the time of the treatment (Creswell, 2014). In this study, the potential threats, description and the action taken to overcome or minimise the threats by the researcher as presented in Table 4.6.

Table 4.6

*Threats to External Validity*

| Threats | Description | Action Taken by Researcher |
|---|---|---|
| Interaction of treatment and history | The result of an experiment is within a time frame, and the result cannot be generalised to future or past situation. | There need to replicate the study at a later date to determine whether the findings are consistent with the previous one |
| Interaction of selection and treatment | The sample used for the experiment is unique to that population. Therefore, the result cannot be generalised to other individuals with different characteristics | The generalisation was restricted to sample and not to other population |
| Interaction of treatment and setting | The setting of this research is unique, and the findings cannot be generalised to other settings. | The researcher will need to carry out another experiment with a different setting to establish whether the present and previous findings are consistent. |
| Experimenter or Researcher effects | Experimenter effect occurs when the students are affected by the researcher consciously or unconsciously. For instance, they are not used to him | The teachers of the students were trained and involved in the treatment. The researcher has no direct contact with the students. |

### 4.5.4 Reliability of Critical Thinking Test

The reliability of a test instrument refers to the degree to which an instrument yields the same or similar results over some time in the same condition or setting; this implies the consistency of test results. The researcher employed a split-half method to pilot test the instrument with a sample of 40 students, the data obtained were calculated using the SPSS, to determine the reliability coefficient of the five sub-skills of critical thinking skills (inference, recognition of assumption, deduction, interpretation, and evaluation). The Cronbach alpha reliability coefficient ranges from 0.71 - 0.75 which is considered acceptable. This result is in agreement with earlier the findings of (Sekaran & Bougie, 2010) who reported that the reliability coefficient of 0.60 is considered as poor, 0.70 is considered acceptable, and 0.80 is considered as good. It is also in agreement with (Tucker, 2007) who reported that a reliability coefficient of 0.50 - 0.80 is considered moderate while above 0.80 it is high. The instrument is attached as Appendix 1.

## 4.6 Genetic Achievement Test (GAT)

GAT was used to collect data to answer question three and five. The test was adopted and adapted by the researcher. The GAT was divided into two sections. Section A gathered data on demographic information of the sample such as age, class, parent's occupation, and gender. Section B comprised of multiple-choice questions that are adapted to gather information on the achievement of students in genetic content. The items of this test are adopted from the West African Secondary School Certificate Examination (WASSCE) and the National Examination Council (NECO) with some minor changes. The West African Examination Council (WEAC) prepare and conduct examination leading to the award of the West African Senior School Certificate Examination (WASSCE) which qualifies students for admission into the university.

The English-speaking countries of West Africa; Ghana, Nigeria, Sierra Leone, Liberia, and the Gambia take part in this examination.

A total of 30 questions consisting of Mendel's first law (lower order questions =2 and higher order question =5), Mendel's second law (lower order questions =2 and higher order question =5) probability (lower order questions =2 and higher order question =5) and genetic terminologies (lower order questions =2 and higher order question =5). This instrument was used as a pre-test and post-test of the research, and the questions are distributed as shown in Table 4.7 below

Table 4.7

*Distribution of genetic achievement test*

| **Content** | **Lower skills** | **Higher Skills** | **Total** |
|---|---|---|---|
| Mendelian First Law | 2 (Q 2 and 5) | 5 (Q 1,3,4,6 &7) | 7 |
| Mendelian Second Law | 2 (Q8 and 13) | 5 (Q9,10,11,12 &14 | 7 |
| Probability | 2 (Q16 & 18) | 5 (Q15,17,19,20 &21) | 7 |
| Genetic Terminologies | 4 (Q26,27, 28 & 29) | 5 (Q22,23,24,25 &28) | 9 |
| **Total** | **10** | **20** | **30** |

Table 4.7 shows the distributions of questions in GAT. There are five objective answers from option A-E for each question where students are expected to select one as the correct answer. The students were given forty-five (45) minutes to answer the questions. One (1) mark was allocated for each correct answer and 0 (zero) for a wrong answer. The total maximum score was thirty (30) marks. The instrument is attached as Appendix 2.

### 4.6.1 The validity of GAT

Validation of GAT is done to make sure the instrument measures what it is supposed to measure. The GAT was validated by two senior secondary school biology teachers who have taught for more than ten (10) years and one expert in psychometric from National Examination Council (NECO), and they provided comments on how to improve the GAT.

### 4.6.2 Reliability of Genetic Achievement Test

The GAT was pilot tested on an intact class of 50 students. These students are part of the population for the research study, but not among the selected sample for the study. The duration of the test was forty-five (45) minutes. One (1) mark was allocated to each correct item and a total maximum score of 30 marks.

The researcher adopted Split-Half Reliability method to check the reliability of GAT. The data was generated and using SPSS 21.0 the researcher calculated the reliability coefficient to be between 0.74 - 0.79. However, Spear-Brown formula was used to improve the reliability of the whole test $\boldsymbol{R = \frac{2r}{1+r}}$ therefore, R= **2(r)/ (1+r).** Hence, Spear man-Brown formula yielded an increased value of 0.84 and this considered acceptable for this research study. This result is supported by the findings of Sekaran and Bougie (2010) who reported that the reliability coefficient of 0.60 is considered as poor, 0.70 is considered acceptable, and 0.8 is considered as good. It is also in agreement with (Tucker, 2007) who reported that a reliability coefficient of 0.50 - 0.80 is considered moderate while above 0.80 it is high. Therefore, the reliability coefficient obtained for this instrument is considered acceptable for this research. Spear-Brown is more appropriate when the items of the instruments are objectively scored, and it estimates the entire reliability of all the items in the instrument (Creswell, 2008), unlike the KR-20 which estimate only half of the item.

## 4.7 Data Collection Procedures

The research procedure was made up of three phases; the pre-intervention, intervention, and post-intervention as highlighted in Table 4.8

*Table 4.8*

*Quantitative Design Layout*

| Group | Pre-intervention<br>1st Week | Intervention<br>Week 2-7 | Post-intervention<br>Week 8 |
|---|---|---|---|
| ISTEMa | Pre-test Critical Thinking Skills | iSTEMa Approach using iSTEMim | Post-test Critical Thinking Skills |
| | Pre-test Genetic Achievement (GAT) | | Post-test Genetic Achievement (GAT) |
| Traditional | Pre-test Critical Thinking Skills | Traditional | Post-test Critical Thinking Skills |
| | Pre-test Genetic Achievement (GAT) | Approach | Post-test Genetic Achievement (GAT) |

### 4.7.1 Pre-intervention Phase

Before treatment, the researcher went to the sampled schools to obtain permission from the school authorities to carry out the research. The permission was obtained, and the duration of the research was eight (8) weeks. The first week, the students and teacher were given an orientation on how to implement iSTEMim,

The teacher acted as a facilitator during iSTEMa implementation. The role of the facilitator was vital for the success of iSTEMa sessions. Therefore, the teacher needed to be trained on how to engage the students effectively using integrated STEM instructional materials (iSTEMim) to achieve the objective of the studies. The researcher explained the objectives of the study, the phases of iSTEMa and what they were expected to do in each phase as well as the activities. The rules of group interaction or brainstorming session were highlighted to the teacher. Three teachers voluntarily indicated interest and were trained in the experimental school, but only one teacher Mallam Abubakar (pseudonym) was used for the study. The researcher went through one task with the teachers. The teachers implemented the iSTEMim because their students may be more relax and open to engaging in the learning process with their regular teacher than a stranger (Hammersley, 1993). The control group was taught by another teacher, Mallam Salisu (pseudonym). The two teachers, Mallam Salisu and Mallam Abubakar, were selected because both have more than ten (10) years teaching experience in teaching biology.

In the iSTEMa group, the students were assigned to a group of five students each with mixed ability and gender so that the high ability group could serve as a scaffold for low ability to learn. Similarly, low ability could ask for explanation which will enhance high ability students' learning. The practice of between class ability (placing students of the same ability in the same class) has been reported to widen the achievement gap between high and low ability students with high ability group doing better than low ability group (Hornby, Witte, & Mitcell, 2011). They opposed between ability grouping because of its negative impact on low ability students. Therefore, mixed ability, that is heterogeneous grouping of the students have been advocated (Khazaeenezhad, Barati, & Jafarzade, 2012; Schofield, 2010). In heterogenous grouping low ability students performed similar and even better than high ability students (Yaki, Saat, Sathasivam, & Zulnaidi, 2019). Given the preceding, The researcher groups the students based on mixed ability.

A group leader and secretary were appointed for each group. On the other hand, the control group engaged in the whole class arrangement which is also made up of different gender and students' abilities. At the end of that first-week pre-test of science, critical thinking test and GAT were administered for both the iSTEMa and traditional group.

### 4.7.2 Intervention for iSTEMa Group

In the second week, treatment commenced and lasted for six weeks, a total of two hours (120 minutes) per week was used for class interaction. The researcher observed the treatment for the iSTEMa group using iSTEMim throughout the period. The students were presented with open-ended problem scenario that requires the students to provide the solution that will best satisfy the client. The students were provided with a worksheet which contains questions relevant to the iSTEMa phases; the engaging problem, generate ideas, design solution, evaluate and improve and communicate findings. The worksheet also provided support to the students and helped them record their ideas. The iSTEMim for the experimental group was characterised by open-ended task, self-directed learning, and individual and collaborative learning activities.

At the beginning (introduction) of the experimental class, the students were presented with an open-ended problem. For example, in Task 1 of the iSTEMim;

*The African savanna wild rabbit called the hare has an estimated length between 41 – 58 cm and the weight between 1.5 – 3 kilograms (kg). The animal is threatened by extinction and gives birth to only one in a year. It has been hunted for its fur and meat. Your group is contacted by a sales representative (marketer) because of popular demand to engineer a unique rabbit.*

The students were given four (4) minutes to read and study the open-ended problem. The students were given the Need to Know Worksheet individually (attached as appendix 14. This worksheet has question prompts such as *what do you know about the problem? What do you need to know about the problem*? Also, *how can we find what we need to know?* The students then meet to brainstorm on what they know about the problem. Thus, the students work individually to answer the questions and meet to collaborate or brainstorm their ideas as a group. The Need to Know Worksheet was used to help activate students' prior knowledge and reflective thinking. The worksheet was also used as a cognitive scaffold to prompt or activate learners' prior knowledge, highlight what you know about the problem elicit students' reflection of their prior knowledge

The first phase of iSTEMa was engaging the problem This was driven by questions such as: analyse the problems into its component parts, establishe the client requirements and constraints, interpret what constitute a pure and unique rabbit and highlight the goal of the problem. The students engage in the problem individually to record their ideas and findings in the corresponding phase one of the worksheet. Each student then met in their respective groups to brainstorm on the problem scenario. At this phase the students would speculate or hypothesised what the solution would look like and proceed to the next phase.

In the second phase which is Generation of Ideas, students were given the freedom and time to search for resources that will help them solve the problem presented. The students generate ideas on genetic laws, principles, and terminology. Students generate ideas on bioengineering procedures and ideas on how the solution which could be a 2D or 3D will look like and the materials needed in the construction individually. The students will generate ideas individually from their textbooks and recommended websites, ideas on Mendel's laws of segregation and independent assortment, principles of dominance and recessive, application of mendels lwas to genetic engineering among others.  Each student articulate his/her position before meeting in a group to brainstorm. During brainstorming, the students will take turns to present their ideas and the members of each group will first decide whether the idea was applicable or not. Among the ideas applicable, the student brainstorm and come up with the ideas that are good. Sometimes, there could be two or three good ideas and the student further brainstorm to decide which one is the best or come up with a new idea from two or three good ideas. The students in each group will brainstorm to decide on the resources to solve the problem using the collaboration worksheet.

*Table 4.9*

*Collaboration Worksheet*

| Ideas Presented | Applicable | Not applicable | Good Ideas | Best Idea Agreed |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

At this phase the teacher facilitates the instruction by attending to students' questions and queries by providing them with question prompts or clues that will assist them make progress. He ensures few students do not dominate the group and ensures all the students participate in the brainstorming session.

Phase three designing solution: The students first translate their ideas into a sketch on paper and interpret their sketches, gather the required materials for designing the solution. The materials for the construction of the solutions were locally sourced such as; cardboard papers, gum, glue, electric cables, wire among others. The solution is a group project, the iterative nature of iSTEMa allows students to visit previous phases to make changes or adjustment to their earlier position. Since students a dealing with a biological phenomenon the solution could be a prototype or a process.

Evaluate the solution is the next phase, this is done to determine whether the goal of solving the problem have been achieved. Evaluation is achieved by answering the following questions base on the prototype or solution; *is the goal of solving the problem achieved? Why and why not? What can be done to improve the solution?* Based on the student assessment, the prototype or solution is improved

Communicate Findings; the students used the items, models and visual aids created as a solution to communicate their findings to the entire class who acts as the client. One student does the communication of findings on behalf of the entire group while the entire group answers questions from the client.

### 4.7.3 The Traditional Group Instruction

The traditional group instruction was teacher driven. The teacher followed the lesson plan and the textbook as a guide for the traditional instructional group The sample of the traditional lesson is attached as Appendix 15: Lesson Plan for Traditional Instruction. Each traditional lesson presentation was divided into; introduction, step 1, 2, and 3, followed by evaluation and conclusion. The teacher introduces the first lesson by highlighting a brief story on Mendel's the father of genetics. The students' previous knowledge was on cell division; meiosis and mitosis. In the first step, the teacher defines genetics and highlight the difference between heredity and variation. The teacher explains Mendel's law of segregation while the students listen and respond to question from the teacher. The teacher gives a graphical illustration to explain Mendel's first law; the first filial generation and second filial generation in the second step. In step three, the teacher performs monohybrid cross to illustrate Mendel's law of segregation; dominant and recessive trait while the student listen. The teacher evaluates the lesson by asking questions on what he has taught. The give a problem on monohybrid cross for the student to answer in the class. The teacher evaluates the lessons based on the objectives of the lessons. In the second lesson the teacher explains Mendel’s law of independent assortment and present problems from the textbook for the students to solve. The traditional group learn for six weeks.

### 4.7.4 Post-Intervention Phase

The post-test critical thinking skills and genetic achievement (GAT) were administered after the intervention at the $8^{th}$ week. Face to face interview was administered in the 8th week to the 9th selected students. The intervention is summarised as presented in Table 4.10

Table 4.10

*Summary of the Research Intervention*

| | iSTEMa Group | Traditional Group |
|---|---|---|
| Pre-intervention | The arrangement of students to groups<br>Orientation<br>Pre-test critical thinking skills and<br>Genetic achievement | It is a whole class<br>Pretest critical thinkin and genetic achievement was administered |
| Introduction | Students presented with an ill-structured scenario<br>Fill in "the need to know worksheet."<br>Students watch a video clip on the engineering design process | The teacher introduces the lesson by highlighting the previous lesson; Meiosis and mitosis |
| Phase 1: Engaging the Problem | Using iSTEMa worksheet students break the problem or analyse the problem to its components<br>Highlight the goal of solving the problem<br>Highlight the constraint of the problem<br>Students brainstorm on the problem | The teacher explains about Mendel the father of genetics |
| Phase 2: Generation of Ideas | Generate ideas on; genetic laws and principles, probability, and terminologies. Bioengineering procedures and how the solution or prototype will look like<br>Brainstorm on the best solution | The teacher explains Mendel's first and second law, principles of dominance and recessive, |
| Phase 3 Designing the solution | Construct the solution or prototype through a group project by applying the ideas generated | The students are presented with dihybrid cross exercise to perform |
| Phase 4: Evaluate and improve | Evaluation of the solution does the solution meet the requirement of the client<br>Is the goal of the project achieved if yes why/ and if no why not? | The students were evaluated baed on the objectives of the lesson |
| Phase5: communication of findings | Communication of the findings by each group at the end of each task | The teacher summarised the main points of the lesson |
| Post-intervention | Post-test critical thinking skills and<br>Genetic achievement (GAT) | |

## 4.8 Qualitative Data Collection

In this study, the qualitative research strand was used to collect data on students' perspective of their learning experiences using integrated STEM approach. It also involves a description of the behaviour of the participants during the learning process. This provided an added advantage for the researcher to gain more knowledge of the process and context of the research study.

### 4.8.1 Qualitative Sampling and Participants

The ten students who participated in the interview sessions were purposefully selected based on gender and student academic abilities. There were (6) males and four (4) females, while high and low achievers were 4, and 6 respectively.

The present study involved senior secondary school students who were in a boarding school, and therefore, permission was sought from the school authority and the parents-teachers' association.

### 4.8.2 Qualitative Data Collection Methods

Two types of qualitative data were collected. They included classroom observations and interview sessions.

### 4.8.3 Interview

The interview sessions were carried out a week after the intervention was completed to ensure that students were able to express their thoughts and ideas about their experiences using the iSTEMim. A semi-structured interview protocol was used. The interview questions were validated by three science educators (One professor, and two senior lecturers) and two senior teachers at Federal Science and Technical College Kuta Niger State. An example of the interview question is *how you will describe learning using iSTEMa*?

Each student was interviewed once, and each interview session lasted about 30 minutes. The interview sessions took place either in the classroom or in the computer laboratory. These places were used because the students use these venues for the intervention. The interviews were recorded using a tape recorder. The interview protocol is attached as Appendix 3.

#### 4.8.4 Observation

Observation is an important aspect of qualitative data collection (Marshall & Rossman, 2011). The observation data might complement the interview data and provide the researcher with the opportunity to draw inferences that may not be achieved with interviews (Maxwell, 2013). The researcher was a non-participant observer, and field notes were taken during the observation. Field notes were collected during observation during the period of the intervention. The classroom observation was carried out in almost every class session except during students' assessment. The researcher observed how students carried out the activities, interacted with peers within and between groups, brainstorming and a group project. The interaction between students and the teacher were also observed. The observation protocol was validated by three science educators (One professor, and two senior lecturers) and two senior teachers at federal science and technical college Kuta Niger State. The observation protocol is attached as Appendix 4.

### 4.9 The Validity of the Qualitative Data

Validity is the procedure employed by the researcher to ensure that the result is credible and can be trustworthy. This can be achieved through the analysis procedure of the researcher. Several strategies have been recommended for the validity of the qualitative findings, such as triangulation, peer reviews and member checks (Creswell & Clark, 2011). In this study triangulation and peer reviews were used.

### 4.9.1 Triangulation

The adoption of several data sources to strengthen the internal validity and support findings is describe as triangulation (Denzin, 1989). Denzin highlighted four types of triangulation; multiple data source, theory, investigator, and methodological triangulation.

Data source triangulation; this involves collecting data in a different context by the researcher, this can be achieved through collecting data on a given research phenomenon at a different location, time or from a different set of people and comparing the results.

The researcher conducted one on one interview with a few selected students and the researcher's observation field notes. The multiple sources of data provide the validity of this research; therefore, including qualitative data collection and analysis strengthened the study by providing internal validity through triangulation.

### 4.9.2 Peer Review

Peer reviewing involve another researcher or researchers analysing the data; it involves reviewing the transcript of the interview and observation, analysis of the data and scrutinising the themes and subthemes. The justification for peer review is to help reduce the researcher's bias and help to provide meaningful insights (Burnard, Gill, Stewart, Treasure, & Chadwick, 2008). In this study, the data analysis was reviewed by some peers (PhD researchers who are pursuing their PhD degrees in the faculty of education) and the supervisors of this study. The data analysis was presented to the peers using a power point. The findings that were reviewed include; themes, emergent themes, their definition, and excerpts. During reviewing some of the peers ask questions for justification and clarity of some of the findings. The observation and comments of the peers that reviewed the analysis were taken into consideration, and some adjustment was made to improve the analysis. Thus, the bias of the researcher could have been minimised.

## 4.10 Method of Data Analysis

In mixed method research, quantitative and qualitative data are analysed with both methods. Quantitative and qualitative data analysis is made up of; preparing the data based on the method of data analysis, analysing the data manually or using software and finally interpreting the results.

### 4.10.1 Quantitative Data Analysis

The data obtained from the research study was subjected to analysis base on the stated research questions and hypotheses. Firstly, the pre and post-test data were screens to determine whether the assumptions of ANCOVA were violated. Kolmogorov-Smirnov and Shapiro-Wilk, Levene’s and MANOVA tests were used as a statistical method to check for normality of the data, homogeneity of variance and homogeneity of regression slope respectively. The homogeneity of variance between the experimental and control group was buttressed with a graphical output (histogram). Descriptive statistics were employed to determine the mean, standard deviation and mean gain within and between groups.

To test the formulated hypotheses; Analysis of Covariance (ANCOVA) and Multivariate analysis of variance (MANOVA) was used to determine the main effects of treatment. 0.05 alpha level was used as the significant level for all the statistical analyses. Cohen's d was used to calculate the effect size to determine the magnitude of the learning gains between groups. The result of the learning gains was interpreted using 0.2 as small effect size, 0.5 as medium effect size and 0.8 as large effect size (Cohen, 1988).

### 4.10.2 Qualitative Data Analysis

The thematic analysis involves identifying, analysing and reporting patterns (themes) within a given data to interpret several parts of the research objective (Boyatzis, 1998). The data analysis process was inductive; moving from specific to more general (Creswell, 2015). It implies that the identified themes are sturdily related to the data. Data analysis occurred in two phases. The first phase was done during the data analysis; the researcher reflected on the qualitative data collected with the view to identifying which data answers which specific research question and improve on the interview questions. Literature has advocated collecting data and analysis should take place simultaneously (Marshall & Rossman, 2011; Maxwell, 2013; Miles & Huberman, 1994; Patton, 2002). Analyses of data to answer the qualitative research questions were presented and buttressed by excerpts from interviews transcript and field notes from observation to serve as evidence. The excerpts from transcripts adopted Jefferson notation, and the conventions are as presented below;

[ ] Statements or words that appear in square parenthesis show the context of the conversation

( ) Empty parenthesis indicate researchers inability to hear what was said

= Equal sign shows that there are a gap and subsequent extension between two interrupted utterances.

(…) Indicate a brief pause of about 3 seconds

(…..)Indicates a long pause

(text)Words in parentheses denote speech that is not clear

The researcher employs the following "Interview" for students interview and "Observation" for observation field notes. Likewise, each excerpt from the data is dated for easy identification. The analysis of data focused on important categories that may have enhanced critical thinking skills among the experimental group (iSTEMa group). The students' participants are provided with privacy using pseudonyms in this qualitative analysis.

a **Data Transcription**

An important feature of qualitative research is to employ audio recording to record interviews or group interaction. These audio recordings are transcribed verbatim into written form (Stuckey, 2014). He highlighted that this action is the first and critical step in quantitative data analysis (Stuckey, 2014). During transcription of data, the researcher noted speech patterns from the interviewees such as ummh…, and aahh…., except in some situation when the response was not within the context. Therefore, in this study, the data from interviews and observation were transcribed verbatim. The sample of the interview transcribed data is attached as Appendix 5. The researcher read through the transcribed data carefully to make meaning and gain an understanding of the data.

b **Open Coding**

This phase involves classifying and probing data based on the choice of dimension that is relevant to the study (Corbin & Strauss, 2008). Open coding is seen as microanalysis because it provided the foundation to develop categories and established a relationship. The coding was based on the research questions; during the data coding, the researcher locates a text segment and assign a code to it at the margin throughout the data set. Example of this statement from a participant. The sample of the open coding was attached as Appendix 6. An example of assigning a code to a statement is as presented in Table 4.11

*Table 4.11*

*Example of Open Coding*

| Transcript | Codes |
|---|---|
| *….We meet regularly in the group to reason on all the ideas presented and ask for more explanation, assess the ideas and take a decision whether the idea is applicable or not*. The idea was selected based on the ground that genetics principles can be applied to solve the problem. | *Brainstorming* |
| *The group work allows everyone to share his ideas uumm.. and provide justification, it was interesting,* and the rule makes it more interesting for example we were instructed not to criticise | *collaboration* |
| We work individually and… *meet in the group to exchange ideas during group discussion help me learn more from my group members* | *Group discussion* |
| We work together as a group to reach agreement on our unique animal | collaboration |

**c Axial Coding and Selective Coding**

Axial coding involves assessing the relationship between the codes, refining and creating categories that may be refined and developed (Nguyen, 2014). It involves grouping similar codes together. This step was followed by axial coding which involves linking relevant codes and data to create several categories. This axial coding forms the first matrix which made up of category and students' excerpts, the students' excerpts are copied and paste it in the corresponding category. Thus, creating an interview matrix which is attached as Appendix 7, while the observation matrix is attached as Appendix 8. The categories were checked to be sure they were mutually exclusive. An example of axial coding is as presented in Table

*Table 4.12*

*Example of Axial Coding*

| Sub-theme | Codes | Excerpts |
|---|---|---|
| Students' interaction | Brainstorming | ….We meet regularly in the group to reason on all the ideas presented through explanation and assessment of the ideas |
| | Collaboration | Group discussion enhance my understanding, I got different views or opinion on genetics and genetic engineering. Group members respond to any idea help you to gain more facts and understanding |
| | Group discussion | We work individually and… meet in the group to exchange ideas during group discussion help me learn more from my group members |
| | Collaboration | We work together to reach an agreement on our unique animal |

This was followed by sorting out relevant codes into possible subthemes or categories and scrutinising the themes based on the excerpts. The themes were named, defined, and the second matrix was produced which was made up of theme, subtheme, and definition.

*Table 4.13*

*An Example of Selective Coding*

| Theme | Category/Sub-theme | Excerpts |
|---|---|---|
| Learning Interaction | Students interaction | *"Group discussion enhance my understanding, I got different views or opinion on genetics and genetic engineering. Group members response to any idea help you to gain more facts and understanding"* |
| | Peer Tutoring | *"I had misconception how traits are inherited, I thought a child inherit one trait from the father and another from the mother, but now I understand from the group leader's explanation that the child inherits half of the trait from each parent".* |
| | Teachers/students interaction | *"Exchanging ideas between my group members and myself, help me learn so much ……… the teacher comes in when we have difficulties, or we are stuck to guide us"* |

The themes seem to be mutually exclusive. The third matrix was the overall matrix from all data sources (interview and observation) and attached as Appendix 9.

The first, second and third matrix was presented to the committee of supervisors for this study and two (2) PhD students in the field of science education for perusal. PhD students have been trained in qualitative research. The themes and subthemes (categories) were improved based on the feedback of the supervisory committee and PhD students. For example, the subtheme "challenging activities" was refined to "engaging activities" similarly the subtheme "instructional procedure" was refined to "instructional guide" while the theme cognitive processes were refined to "promote cognitive processes" among others. The themes were finally used in writing the report. The qualitative data analysis is summarised into; open coding, pattern and categories identification and naming themes (Miles & Huberman, 1994; Strauss & Corbin, 1990) as presented in Figure 4.4

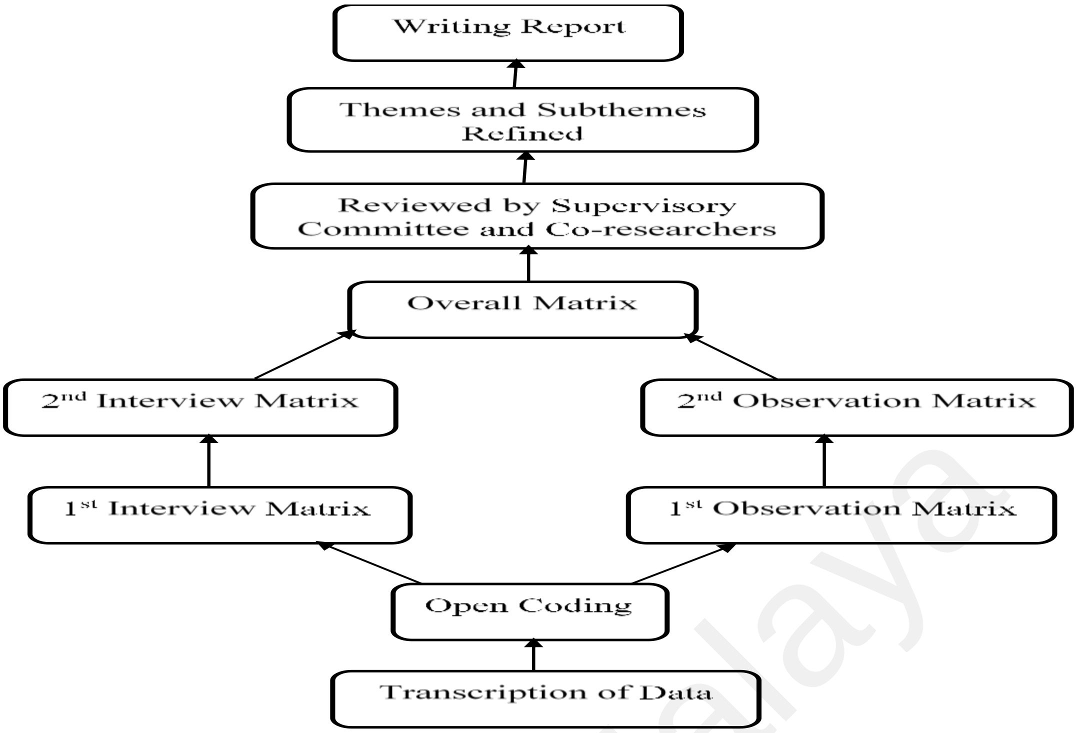


*Figure 4.4. Flow Chart of* Qualitative Data Analysis

The summary of the research procedure which includes pre-intervention, intervention, and post-intervention is as presented in Figure 4.5

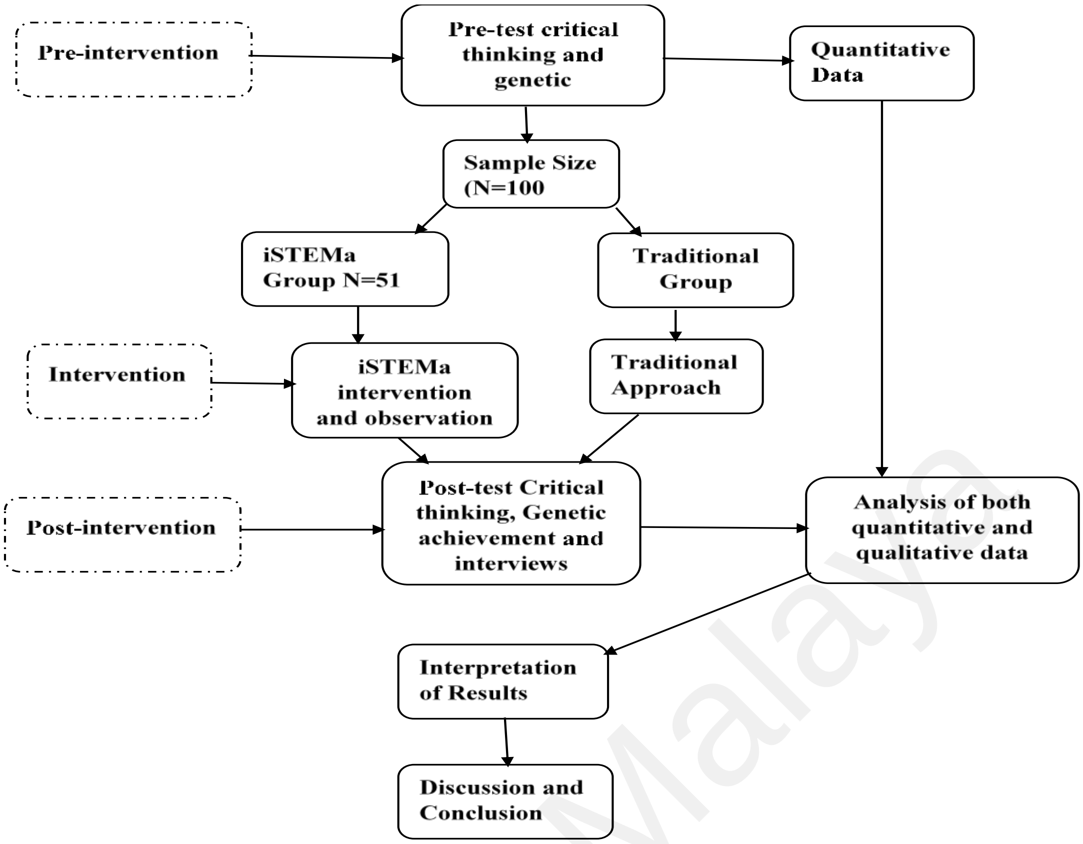


*Figure 4.5. Flowchart of Research Procedures*

## 4.11 Ethical Consideration

Ethics are accepted practices and principles that are correct and acceptable in a given vocation or profession. In research, ethical consideration involves adhering to basic research ethics such as permission to carry out the research, integrity, honesty, and confidentiality of data collected from the participants(Gajjar, 2013; Hammersley, 2015). This protects potential harm to the participants of the study.

The ethical procedure applied before the data was collected in this research includes;

i) A letter seeking permission to conduct the research was sent to the relevant authorities and attached as Appendix 11

ii) Permission to conduct the research was obtained from the secondary schools and is attached as Appendix 12 and 13

iii) A consent letter was given to each participants seeking their approval and informing them that they can withdraw at any time from the research without any penalty and information collected from them will be used primarily for this research.

### 4.12 Chapter Summary

This chapter focused on the research methodology that was adopted for the study. Concurrent or convergent mixed method design, both quantitative and qualitative data were collected concurrently. Two schools in Niger state, Nigeria were purposely selected and randomly assigned to the iSTEMa (experimental) and traditional (control) group. One hundred (100) students make up the sample size for the study; iSTEMa group was fifty-one (51) while the traditional group was forty-nine (49). The quantitative data were collected using science critical thinking instrument developed by the researcher and GAT. Verbal (interviews) and non-verbal (observation) data were collected as qualitative data. The quantitative data were analysed using descriptive and inferential statistics, while the qualitative data was analysed thematically. It is important to highlight that data analysis occur in two phases; the first phase was the quantitative data analysis and the second phase was the qualitative data analysis. The validity and reliability of the instruments were presented.

# CHAPTER 5

# FINDINGS

## 5.1 Introduction

This study determined the effectiveness of integrated STEM approach towards secondary students' critical thinking skills and achievement in genetics. Results and findings associated with the stated research questions and formulated hypotheses are presented. The following research questions were stated to guide the study as reported in chapter one;

1. What are the elements embedded in iSTEMa instructional materials that could promote senior secondary school students' critical thinking skills and genetic achievement?
2. a) Is there any significant mean difference in critical thinking skills between senior secondary school students that learn with iSTEMa (experimental group) and those who learn using the traditional method (control group)?

   b) How does the iSTEMa enhance critical thinking skills among senior secondary school students?
3. a) Is there any significant mean difference in genetic achievement between senior secondary school students that learn with iSTEMa and those who learn using the traditional method?

   b) How does the iSTEMa improve genetic achievement among senior secondary school students
4. Are there any significant interaction effects between students' ability (high, and low) and instructional approach (iSTEMa and traditional approach) on senior secondary school students' critical thinking skills?

5. Are there any significant interaction effects between students' ability (high, and low) and instructional approach (iSTEMa and traditional approach) on senior secondary school students' achievement in genetics?

6. What are the learning experiences of the senior secondary school students upon using iSTEMa to learn?

## 5.2 Quantitative Findings

The pre-test and post-test data for critical thinking skills and students' achievement in genetics were collected to answer the research questions and test the research hypotheses. The quantitative results were presented in the following sequence;

1. Testing of assumption to determine the normality distribution, homogeneousness of variance, and homogeneity of regression slope.
2. Descriptive analysis (mean, standard deviation and mean gain)
3. Inferential statistics (t-test, ANCOVA, and MANOVA) (Creswell, 2014; Piaw, 2013)

The data collected was scored base on the scoring procedures highlighted in the methodology and was subjected to analysis using the Statistical Package for Social Science (SPSS) Version 21. The results are as presented below

## 5.3 Pre-test Critical Thinking Skill

There was a need to establish the level of both the iSTEMa and traditional group in critical thinking skill before the intervention. Therefore, the critical thinking skill test (Appendix 1) was administered to the selected sample as described in the methodology. The pre-test data obtained was subjected to data screening to determine whether the data satisfied the assumption for the use of inferential statistics such as ANCOVA and MANOVA. Therefore, the need to check for normality and homogeneity of variances and homogeneity of regression slope for critical thinking skills.

### 5.3.1 Normality Test

Normal distribution of the critical thinking test scores of iSTEMa and the traditional group was investigated to test the assumption of normality, and the result was presented numerically as well as graphically for each group. Kolmogorov-Smirnov test and Shapiro-Wilk Test was the numerical method employed. The result is as shown in Table 5.1

Table 5.1

*Pre-test Kolmogorov-Smirnov Test and Shapiro-Wilk Test for iSTEMa and Traditional Group Distribution for Normality*

| | **Kolmogorov-Smirnov[a]** | | | **Shapiro-Wilk** | | |
|---|---|---|---|---|---|---|
| | Statistic | Df | Sig. | Statistic | Df | *P-value* |
| iSTEMa | .09 | 49 | .200* | .98 | 49 | .40 |
| Traditional | .14 | 49 | .13 | .97 | 49 | .36 |

*This is a lower bound of the true significance.

Table 5.1 indicates that the Shapiro-Wilk test for iSTEMa was $F$ (49) =982, $p$ (.40) >.05, the p-value (,40) was greater than .05, which indicate the assumption of normality was not violated. The traditional group, Shapiro-Wilk test, was $F$ (49) =972, $p$ (.36) >.05, the p-value (,36) was greater than .05, which indicate that assumption of normality was not violated. The result showed that the observed distribution is approximately normal for critical thinking test score for the two groups. This agrees with Razali and Wah (2011) who reported that "the Shapiro-Wilk test is the most powerful test for all types of distribution and sample sizes."

Therefore, the assumption of normality was not violated; the data were analysed using inferential statistics to test the formulated hypotheses. The result is further presented in a visual output to highlight a normal curve on the histogram. The histogram of the iSTEMa group is as shown in Figure 5.1

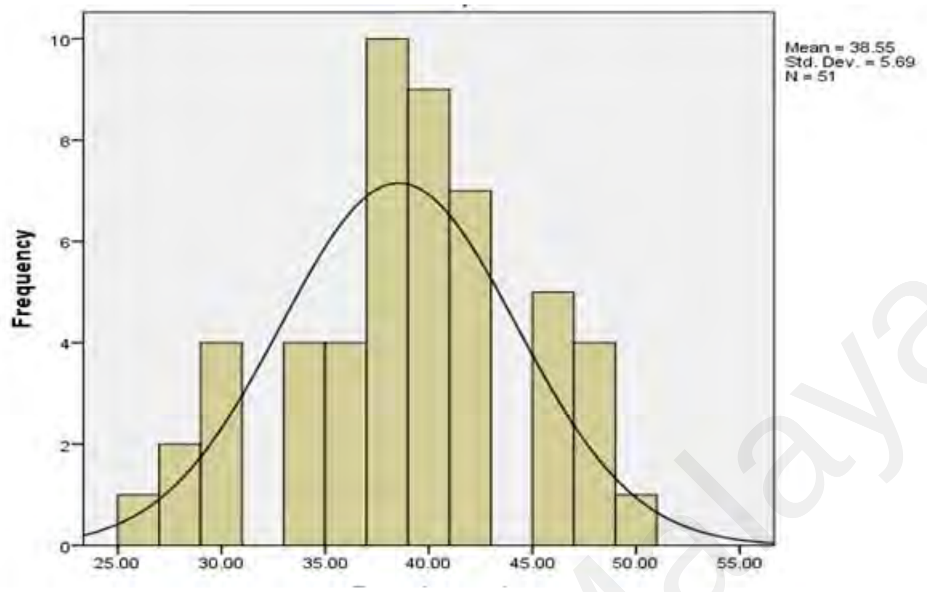


*Figure 5.1.* Histogram and Normal Curve of Pre-test Critical Thinking Skill for iSTEMa Group

The histogram of critical thinking skill normality for the traditional group is as shown in Figure 5.2

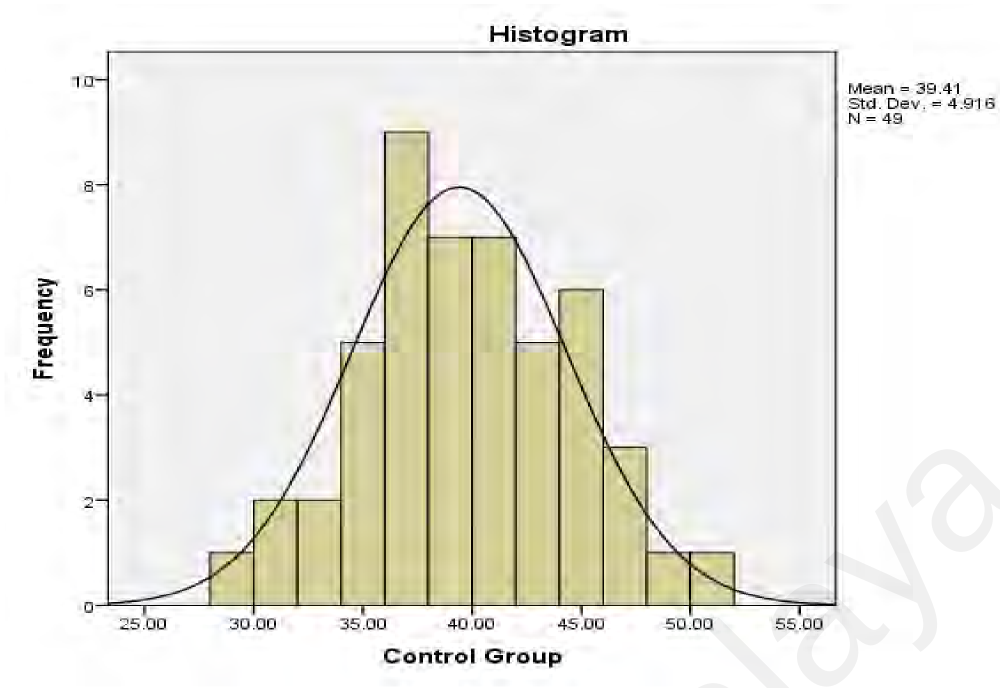


*Figure 5.2.* Histogram of Pre-test critical thinking skill for Traditional Group

Figure 5.1 and 5.2 shows the Histogram visual output of the iSTEMa and traditional group normality respectively, the visual histogram output has a reasonably accurate shape of a normal curve based on the Kolmogorov-Smirnov test and Shapiro-Wilk output. Therefore, it can be assumed that the critical thinking skills post-test data of the two groups are approximately normally distributed.

### 5.3.2 Homogeneity of Variance

Homogeneity of the variance in the pre-test score of critical thinking skills between the iSTEMa and traditional group was determined using Levene's test, and the result is as presented in Table 5.2

*Table 5.2*

*Test of Homogeneity of Variances for Pre-test Critical Thinking Sub-skills between iSTEMa and traditional group*

| | Levene's Statistic | *df1* | *df2* | *P*-value |
|---|---|---|---|---|
| Inference | 1.86 | 1 | 98 | .17 |
| Recognition of Assumption | 1.76 | 1 | 98 | .18 |
| Deduction | 1.54 | 1 | 98 | .21 |
| Interpretation | 0.49 | 1 | 98 | .48 |
| Evaluation Argument | 3.49 | 1 | 98 | .06 |
| Overall Score | .691 | 1 | 98 | .408 |

The result in Table 5.2 clearly shows the findings of pre-test critical thinking subskills of the inference $F(1, 98) = 1.86$, $p = (0.17)$. The *p-value* is greater than 0.05, indicating no significant difference in the variance of inference subskill between iSTEMa and traditional group. Hence, the two groups score are approximately similar. The result of the recognition of assumption shows $F(1, 98) = 1.76$, $p = (0.18) > 0.05$ which shows no significant difference between the iSTEMa and traditional group variance in the critical thinking subskill of recognition of assumption. Therefore, the two groups score are approximately homogeneous.

In deduction subskill pre-test, the result revealed $F(1, 98) = 1.54$, $p = (0.21) > 0.05$. Indicating there is no significant difference between the two groups (iSTEMa and traditional group) in deduction subskill of critical thinking. Therefore, the two groups score are approximately identical.

Pre-test interpretation subskill result was $F(1, 98) = 0.492$, $p = (0. 485)$ which is greater than 0.05, which means there is no significant difference between the two group (iSTEMa and traditional group) variance in interpretation subskill. Evaluating arguments was $F(1, 98) = 3.49$, $p = (0.65) > 0.05$ which shows no significant difference between the iSTEMa and traditional group variance in evaluation of arguments subskill. Therefore, the two groups score are approximately homogeneous.

The overall pre-test critical thinking score on Table 5.2 clearly shows that the critical thinking skill score homogeneity of variance for iSTEMa and the traditional group was $F(1, 98) = .691$, $p = (0.40)$ which is greater than 0.05. Indicating there is no significant difference between the two groups variance in critical thinking skills. Therefore, the two group scores are approximately homogeneous.

### 5.3.3 Homogeneity of Regression Slope for Critical thinking skills

The test for homogeneity of regression slope determines whether the independent variables have parallel regression slope, indicating that there is a similar covariate slope for the two groups. If the result yields interaction effects, then the assumption for the use of ANCOVA is violated.

The independent variables are the two groups iSTEMa and traditional group. The dependent variable is the post-test of the overall critical thinking skill score and the subskills: interpretation, recognising assumption and deduction, As well as interpretation, and evaluating information. While the covariate is the pre-test scores. The results for homogeneity of regression slope for critical thinking skill for the iSTEMa and traditional group is as presented in Table 5.3

Table 5.3

*Pre-test Result Homogeneity of Regression Slope for iSTEMa and Traditional Group on Critical Thinking Skills*

| Source | Dependent Variable | *Df* | Mean Square | *F* | *P*-value |
|---|---|---|---|---|---|
| Groups | Inference | 1 | 124.36 | 10.25 | .01 |
| | Recognizing Assumption | 1 | 3.65 | .36 | .54 |
| | Deduction | 1 | 31.51 | 2.49 | .11 |
| | Interpretation | 1 | 31.53 | 2.34 | .12 |
| | Evaluating Arguments | 1 | .00 | .00 | .98 |
| | Overall Score | 1 | 587.94 | 8.14 | .01 |
| Groups * pre-Inference * Assumption * Deduction * Interpretation * Eva_Arguments* PreTotal | Inference | 2 | 20.23 | 1.66 | .19 |
| | Recognizing Assumption | 2 | 2.57 | .25 | .77 |
| | Deduction | 2 | 1.86 | .14 | .86 |
| | Interpretation | 2 | 6.27 | .46 | .62 |
| | Evaluating Arguments | 2 | 20.80 | 3.07 | .05 |
| | Overall Score | 2 | 38.81 | .53 | .58 |
| Error | Inference | 96 | 12.13 | | |
| | Recognizing Assumption | 96 | 10.03 | | |
| | Deduction | 96 | 12.63 | | |
| | Interpretation | 96 | 13.42 | | |
| | Evaluating Arguments | 96 | 6.76 | | |
| | Overall Score | 96 | 72.19 | | |

Table 5.3 shows the homogeneity of regression slope of variance for inference subskill of critical thinking skills of the iSTEMa and traditional group $F(2, 96) = 1.668$, $p(.194) > .05$. We fail to reject the assumption. Indicating that the assumption of homogeneity of regression slope of variance was not violated. Therefore, ANCOVA was used to analyse the data

The homogeneity of regression slope results for recognising assumption subskill of critical thinking skills was $F(2, 96) = .256$, $p$ $(.774) > .05$. We fail to reject the assumption. Indicating that assumption of homogeneity of regression slope of variance was not violated. The homogeneity of regression slope results for deduction subskill of critical thinking skills was $F(2, 96) = .148$, $p(.863) > .05$. Indicating that assumption of homogeneity of regression slope of variance was not violated

The results for interpretation subskill of critical thinking skills was $F(2, 96) = .486$, $p(.628) > .05$. We fail to reject the assumption. Indicating that assumption of homogeneity of regression slope of variance was not violated. The homogeneity of regression slope results for evaluating arguments subskill of critical thinking skills was not violated $F(2, 96) = 3.073$, $p(.051) > .05$. The overall critical thinking skill results shows *F-ratio* for the interaction $F(2, 96) = .583$, $p(.586) > .05$. Indicating that there was no violation of the assumption. It is, therefore, concluded that the independent variables (iSTEMa and traditional group) have parallel regression slope. Therefore, MANOVA was used to analyse the results.

### 5.3.4 Pre-test Results for Critical Thinking Skills of iSTEMa and Traditional Group

To determine whether the groups were equivalent or similar in critical thinking skills before the intervention, data were collected using a critical thinking pre-test. A MANOVA was employed to determine whether the iSTEMa and traditional group were equivalent in all the sub-skills of critical thinking before the intervention. The result is as presented in Table 5.4 below

Table 5.4

*Pre-test Critical Thinking Skill of iSTEMa and Traditional Group*

| Effect | | Value | F | Hypothesis df | Error df | Sig. |
|---|---|---|---|---|---|---|
| Intercept | Pillai's Trace | .98 | 1054.25 | 5.00 | 92.00 | .01 |
| | Wilks' Lambda | .01 | 1054.25 | 5.00 | 92.00 | .01 |
| | Hotelling's Trace | 57.29 | 1054.25 | 5.00 | 92.00 | .01 |
| | Roy's Largest Root | 57.29 | 1054.25 | 5.00 | 92.00 | .01 |
| Groups | Pillai's Trace | .05 | 1.16 | 5.00 | 92.00 | .33 |
| | Wilks' Lambda | .94 | 1.16 | 5.00 | 92.00 | .33 |
| | Hotelling's Trace | .06 | 1.16 | 5.00 | 92.00 | .33 |
| | Roy's Largest Root | .06 | 1.16 | 5.00 | 92.00 | .33 |

Table 5.4 reveals MANOVA result of the pre-test critical thinking skill, using Wilk's Lambda test with .05 alpha level, the findings indicated there was no significant difference between the iSTEMa and traditional group in all critical thinking subskills; inference, recognition of assumption, deduction, interpretation, and evaluation of arguments Wilks' $\wedge$ = .94, $F(5, 92)$ =1.16, $p$ = (.33) > 0.05. The mean of the overall critical thinking skill between the iSTEMa and traditional group is 38.54 and 39.46 respectively. Therefore, the test of between-subject effects was presented to buttress the results Table5.5.

*Table 5.5*

*Pre-test of Between-Subject Effects of iSTEMa and Traditional Group on Genetic Achievement*

| Source | Dependent Variable | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Intercept | Inference | 1 | 3616.71 | 505.85 | .01 |
| | Recognizing Assumption | 1 | 5223.44 | 1003.30 | .01 |
| | Deduction | 1 | 7720.79 | 961.07 | .01 |
| | Interpretation | 1 | 4716.06 | 653.85 | .01 |
| | Evaluating arguments | 1 | 8611.02 | 2021.23 | .01 |
| | Overall Score | 1 | 145732.88 | 5139.76 | .01 |
| Groups | Inference | 1 | 18.67 | 2.61 | .10 |
| | Recognizing Assumption | 1 | 5.72 | 1.10 | .29 |
| | Deduction | 1 | 8.41 | 1.04 | .30 |
| | Interpretation | 1 | 3.82 | .53 | .46 |
| | Evaluating arguments | 1 | 1.20 | .28 | .59 |
| | Overall Score | 1 | 21.83 | .77 | .38 |
| Error | Inference | 96 | 7.15 | | |
| | Recognising Assumption | 96 | 5.20 | | |
| | Deduction | 96 | 8.03 | | |
| | Interpretation | 96 | 7.21 | | |
| | Eva of arguments | 96 | 4.26 | | |
| | Overall Score | 96 | 28.35 | | |

Table 5.5 shows the between-subject effects of the critical thinking subskills of inference, recognising assumption deduction, interpretation and evaluation of arguments of the iSTEMA and traditional group before treatment. The result indicates that there was no significant difference between the iSTEMa and traditional group in all the dimensions ($p > .05$). The overall score also indicated no significant difference; $F(1, 96) = .77$, $p = (0.38) > 0.05$. Therefore, the two groups were comparable in their critical thinking skills before the treatment.

## 5.4 Pre-test Genetic Achievement Test

Before the intervention, there was the need to establish the level of the iSTEMa and traditional group achievement in genetics. Therefore, the genetic achievement test was administered to the selected sample for the study as described in the methodology. The data obtained was subjected to data screening for normality, homogeneity of variance and homogeneity of regression slope as well as t-test to determine their equivalence

### 5.4.1 Normality Test

Normal distribution of the genetic achievement test scores of iSTEMa and the traditional group was investigated to test the assumption of normality, and the result presented numerically and graphically for each group. Kolmogorov-Smirnov test and Shapiro-Wilk test was the numerical method employed to check for normality. The result is as presented in Table 5.6

Table 5.6

*Normality Test for Pre-test iSTEMa and Traditional Group Genetic Achievement*

| | **Kolmogorov-Smirnov[a]** | | | **Shapiro-Wilk** | | |
|---|---|---|---|---|---|---|
| | Statistic | *Df* | Sig. | Statistic | *df* | *P-value* |
| iSTEMa | .100 | 51 | .200* | .965 | 51 | .137 |
| Traditional | .108 | 49 | .200* | .975 | 49 | .389 |

Table5.6 indicates that the Pre-test Shapiro-Wilk test for iSTEMa group was *F* (51) = 965, *p* (.13) >.05, which suggest that there no violation of the assumption of normality. The traditional group, Shapiro-Wilk test, was *F* (49) =975, *p* (.38) >.05, which indicate the assumption of normality was not violated. Similarly, the *p-value* of the Kolmogorov-Smirnov test was higher than .05 (*p*>.05) The result indicated that the observed distribution is approximately normal for critical thinking test score for the

two groups (iSTEMa and traditional group). Therefore, the data is said to be approximately normal, since the assumption of normality was not violated, the data were analysed using parametric statistics. Figure 5.3 and 5.4 visually verify the assumption of normality for the iSTEMa and traditional group respectively as presented below.

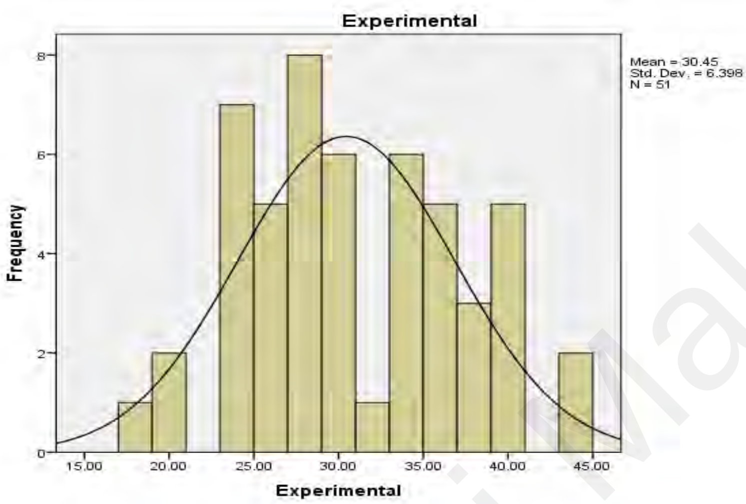


*Figure 5.3.* Pre-test Histogram and normal curve for iSTEMa group

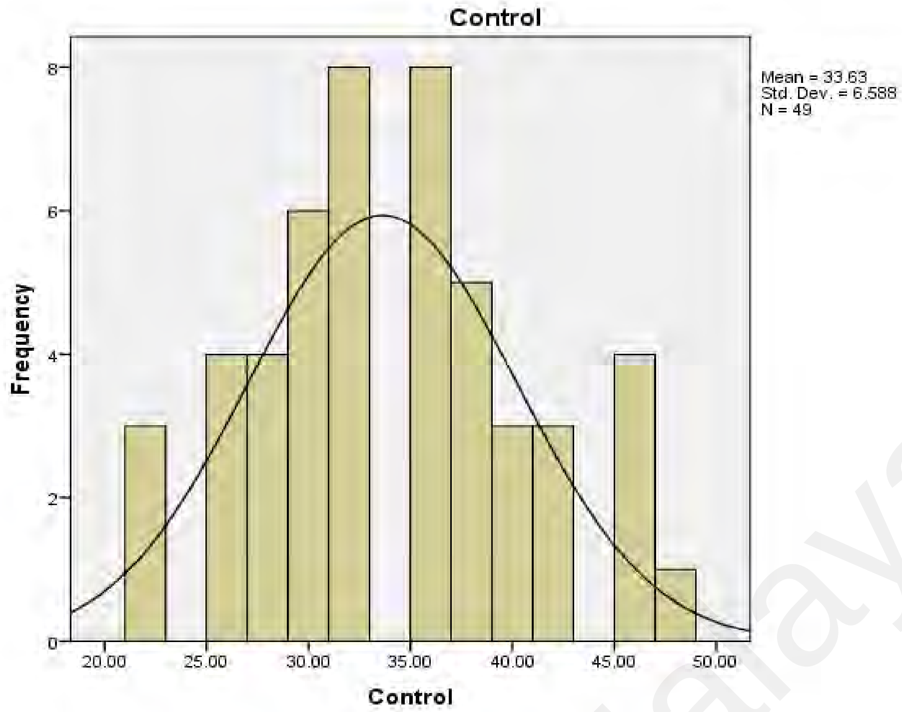


*Figure 5.4.* Pre-test Histogram and normal curve of genetic achievement test for Traditional Group

The shape of the iSTEMa and traditional group histogram of genetic achievement students' scores shows that the data distribution is approximately normal. Thus, there was no violation of the assumption of normality.

### 5.4.2 Homogeneity of Variance

The assumption for homogeneity of variance of genetic achievement test subsections of genetic terminology, Mendel's laws and genetic probability between iSTEMa and the traditional group was determined using Levene's test. The result is presented in Table 5.7.

Table 5.7

*Pre-test Levene's Test for Homogeneity of Variances*

| Genetic Achievement | Levene Statistic | *df1* | *df2* | *P*-value |
|---|---|---|---|---|
| Terminology | .16 | 1 | 98 | .68 |
| Mendel's laws | .96 | 1 | 98 | .32 |
| Probability | .00 | 1 | 98 | .95 |
| Overall | 0.28 | 1 | 98 | .86 |

The result in Table 5.7 displays the Pre-test genetic achievement dimensions of iSTEMa and the traditional group which includes; terminology is $F(1, 98) = 0.16$, $p$= (0.68), which shows no significant difference in the variances between the two group in genetic terminology.

The Pre-test result of Mendel's laws shows $F(1, 98) = 0.96$, $p = (0.32) > 0.05$, which shows no significant difference between the iSTEMa and traditional group in Mendel's Laws subsection. In probability subsection the result revealed $F(1, 98) = 0.03$, $p = (0.95) > 0.05$ which shows no significant difference between the two group (iSTEMa and traditional Group) in Probability subsection of genetic achievement in the pre-test.

The overall Pre-test results between the iSTEMa and traditional group in the pre-test genetic achievement are $F(1, 98) = 0.28$, $p = (0.86)$ indicates that there is no significant difference between the variances of the two groups in genetic achievement and the three subsections (Genetic Terminology, Mendel's Laws and Probability). Hence, the variances of the groups are approximately equal before the mediation.

### 5.4.3 Homogeneity of Regression Slope for Genetic Achievement

The independent variables are the two groups iSTEMa and traditional group, and the dependent variable is the genetic achievement score; genetic terminology, Mendel's laws, genetic probability and the overall score for pre-test and post-test. While the covariates are the pre-test score. The results for homogeneity of regression slope for genetic achievement score for the iSTEMa and traditional group is as presented in Table 5.8

Table 5.8

Pre-test *Homogeneity of Regression Slope for Genetic Achievement*

| Source | Dependent Variable | *df* | Mean Square | *F* | *P-value* |
|---|---|---|---|---|---|
| Group | Terminology | 1 | 29.91 | 4.24 | .04 |
| | Mendel's Laws | 1 | 21.63 | 1.17 | .28 |
| | Probability | 1 | .17 | .01 | .89 |
| | Overall Score | 1 | .16 | .00 | .95 |
| Group* Terminology* Mendel's laws* Probability * Overall | Terminology | 2 | 53.47 | 7.58 | .01 |
| | Mendel's Laws | 2 | 10.77 | .58 | .56 |
| | Probability | 2 | 8.18 | .81 | .44 |
| | Overall Score | 2 | 71.94 | 1.63 | .20 |
| Error | Terminology | 96 | 7.04 | | |
| | Mendel's Laws | 96 | 18.43 | | |
| | Probability | 96 | 9.98 | | |
| | Overall Score | 96 | 44.03 | | |

Table 5.8 shows the Pre-test homogeneity of regression slope variance of the two groups in genetic terminology. The result was $F(2, 96) = 7.58$, p (.00) >.05. We reject the assumption, indicating that there was no violation of the assumption of homogeneity of regression slope of variance. The homogeneity of regression slope results of the two groups in Mendel's laws subsection of genetics was $F(2, 96) = .584$, p (.56) >.05. We fail to reject the assumption. Indicating that there was no violation of the assumption of homogeneity of regression slope of variance. The results for

probability was *F*(2, 96) = .82, p (.444) >.05. Indicating that there was no violation of the assumption.

The overall Pre-test results of the two groups show *F-ratio* for the interaction *F*(2, 96) = 1.634, *p*(.20) >.05. Indicating that there are no statistical interaction effects which did not violate the assumption for homogeneity of regression slope. It is, therefore, concluded that the independent variable has a parallel regression slope. Even though there is a minor violated of the assumption in the subsection of genetic terminology the overall result indicated there was no violation of the homogeneity of regression slope. Therefore, MANOVA was used to analyse the results because it is robust enough to accommodate the minor violation since the assumption of normality and homogeneity of variance were not violated (Johnson, 2016).

### 5.4.4 Pre-Test Result of Genetic Achievement for the iSTEMa and Traditional Group

The iSTEMa and traditional group mean and standard deviation for all the three subsections (Genetic Terminology, Mendel's Laws and Probability) were determined. A MANOVA was employed to determine whether the iSTEMa and traditional group were equivalent in all the sub-section and the overall score in genetics before the intervention. The result is as displayed in Table 5.9

Table 5.9

*Pre-test Result of iSTEMa and Traditional Group in Genetic Achievement*

| Effect | | Value | *F* | Hypothesis *df* | Error *df* | *P*-value |
|---|---|---|---|---|---|---|
| Intercept | Pillai's Trace | .96 | 636.78[b] | 4.00 | 95.00 | .01 |
| | Wilks' Lambda | .03 | 636.78[b] | 4.00 | 95.00 | .01 |
| | Hotelling's Trace | 26.81 | 636.78[b] | 4.00 | 95.00 | .01 |
| | Roy's Largest Root | 26.81 | 636.78[b] | 4.00 | 95.00 | .01 |
| Group | Pillai's Trace | .20 | 6.20[b] | 4.00 | 95.00 | .01 |
| | Wilks' Lambda | .79 | 6.20[b] | 4.00 | 95.00 | .01 |
| | Hotelling's Trace | .26 | 6.20[b] | 4.00 | 95.00 | .01 |
| | Roy's Largest Root | .26 | 6.20[b] | 4.00 | 95.00 | .01 |

Table 5.9 reveals MANOVA result of the pre-test genetic achievement, using Wilk's Lambda test with .05 alpha level the findings indicated there was a significant difference between the iSTEMa and traditional group in genetic achievement; genetic terminology, Mendel's laws, and probability. Wilks' ʌ = .26, $F$ (4, 95) = 6.20, $p$ = (.00) < 0.05. The overall mean of the iSTEMa and the traditional group were 30.45 and 33.59 respectively. The significant difference was in favour of the traditional group. The between-subjects effect for each dependent variable was presented to buttress the result as presented in Table5.10

*Table 5.10*

*Test of Between-Subject Effects of iSTEMA and Traditional Group on Genetic Achievement*

| Source | Dependent Variable | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Intercept | Terminology | 11366.51 | 1 | 11366.51 | 1578.55 | .01 |
| | Mendel's laws | 10763.30 | 1 | 10763.30 | 1476.57 | .01 |
| | Probability | 10393.55 | 1 | 10393.55 | 1991.86 | .01 |
| | Overall Score | 98559.84 | 1 | 98559.84 | 2294.59 | .01 |
| Group | Terminology | 125.71 | 1 | 125.71 | 17.45 | .01 |
| | Mendel's laws | 4.67 | 1 | 4.67 | .64 | .42 |
| | Probability | 3.25 | 1 | 3.25 | .62 | .43 |
| | Overall Score | 232.24 | 1 | 232.24 | 5.40 | .02 |
| Error | Terminology | 691.25 | 96 | 7.20 | | |
| | Mendel's laws | 699.78 | 96 | 7.28 | | |
| | Probability | 500.92 | 96 | 5.21 | | |
| | Overall Score | 4123.49 | 96 | 42.95 | | |

Table 5.10 shows the between-subject comparison of the genetic subsection of the iSTEMA and traditional group before treatment. The result indicates that there was a significant difference between the iSTEMa and traditional group in genetic terminology dimension $F(1, 96) = 17.45$, $p = (0.00) < 0.05$, with the mean of the traditional group (12.08) was higher than the mean of the iSTEMa group (9.78). There was no significant difference between the two groups in Mendel's law and Probability; $F(1, 96) = .64$, $p = (.42) > 0.05$, and $F(1, 96) = .62$, $p = (0.43) > 0.05$ respectively. The overall genetic achievement in the pre-test between the iSTEMa and traditional group shows $F(1, 96) = 5.40$, $p = (0.02) < 0.05$, indicating a significant difference between the two groups before the commencement of treatment.

## 5.5 Pre-test Result of High and Low Achievers in Critical Thinking Skills

The data high and low achievers were screened for the assumption of normality, homogeneity of variance and homogeneity of regression slope before the pre-test data were analysed. The findings are as presented below;

### 5.5.1 Normality Test

Normal distribution of the critical thinking test scores of high and low achievers of the iSTEMa and the traditional group was investigated to test the assumption of normality, and the result presented numerically. Shapiro-Wilk Test was the numerical method employed because the sample size for each group was less than fifty (n<50). This is supported by (Warner, 2013) who reported that Shapiro-Wilk test is appropriate when the sample size is less than fifty (n<50) while Kolmogorov-Smirnov test is appropriate when the sample size is greater than fifty (n>50). The result is presented in Table 5.11.

Table 5.11

*Pre-test Critical Thinking skill of High, and Low Achievers of the iSTEMa and Traditional Group*

| | | Shapiro-Wilk | | |
|---|---|---|---|---|
| | Ability | Statistic | *Df* | *P*-value |
| Critical thinking skills | iSTEMaHA | .952 | 20 | .39 |
| | iSTEMaLA | .953 | 31 | .19 |
| | *TradHA* | .968 | 19 | .73 |
| | *TradLA* | .947 | 30 | .14 |

*iSTEMa High Achievers (iSTEMaHA), iSTEMa Low Achievers (iSTEMaLA), traditional High Achievers (TradHA), and traditional Low Achievers (TradLA)*

Table 5.11 reveals the Shapiro Wilk's test result of the iSTEMa Group High Achievers (iSTEMaHA) were $F(20) = .952$, $p(.39) > .05$, which indicates that the data is approximately normally distributed. The iSTEMa Group Low Achievers (iSTEMaLA) result shows that $F(31) = .953$, $p(.19) > .05$, which indicates that the data is approximately normally distributed. The Traditional Group High Achievers (*TradHA*) and Traditional Group Low Achievers (*TradLA*) indicates $F(19) = .968$, $p(.73) > .05$, and $F(10) = .953$, $p(.69) > .05$ respectively, which indicates that the data is approximately normally distributed. Therefore, the result of the high and low achievers for the iSTEMa and traditional group did not violate the assumption of normality.

### 5.5.2 Levene's Test for Homogeneity of Variances for High, and Low Achievers

The assumption of variance was checked using Levene's test for high, and low ability achievers for the iSTEMa and traditional group. The result is as presented in Table 5.12

Table 5.12

*Levene's Test for Homogeneity of Variances for Pre-test score of High and Low Achievers of Experimental and Control*

| | Levene Statistic | df1 | df2 | *P*-value |
|---|---|---|---|---|
| Inference | 1.71 | 3 | 96 | .16 |
| Recognizing Ass | 1.20 | 3 | 96 | .31 |
| Deduction | 1.29 | 3 | 96 | .27 |
| Interpretation | 1.86 | 3 | 96 | .14 |
| Evaluating arguments | 1.89 | 3 | 96 | .13 |
| Overall | 1.20 | 3 | 96 | .31 |

Table 5.12 reveals the result of Levene's test for homogeneity of variances for the high and low achievers for iSTEMa and traditional group.

The result indicates that the *p-value* in all the pre-test five subskills of critical for the high and low achievers of the two groups are not significant *(p>.05)*. The overall critical thinking score was $F(3, 96) = 1.205$, $p(.31) > 0.05$. It can be inferred that there are no significant differences between the variances of high and low achievers of the iSTEMa and traditional group. The variances of the groups are approximately equal in the pre-test of critical thinking skills. Therefore, the assumption for homogeneity of variance was not violated; the data were analysed as planned.

### 5.5.3 Homogeneity of Regression Slope for Pre-test Critical thinking skills of High and Low Ability

The independent variables are high and low achievers of the iSTEMa and traditional group. The dependent variable is the post-test of the overall critical thinking skill and the subskills: interpretation, recognising assumption, deduction, as well as interpretation, and evaluation of information. While the covariate is the pre-test score. The results for homogeneity of regression slope for critical thinking skill score for the high and low achievers of iSTEMa and the traditional group is as presented in Table 5.13

Table 5.13

*Pre-test Homogeneity of Regression Slope of High and Low Ability Students' Critical Thinking Skills*

| Source | Dependent Variable | df | Mean Square | F | *P*-value |
|---|---|---|---|---|---|
| Ability* Inference * Recognizing Assumption* Deduction* Interpretation* Evaluating Arguments* Total_CTSpre | Overall Score | 2 | 109.48 | 1.38 | .25 |
| | Inference | 2 | 1.56 | .11 | .89 |
| | Recognizing Assumption | 2 | .79 | .07 | .92 |
| | Deduction | 2 | 6.67 | .50 | .60 |
| | Interpretation | 2 | 10.07 | .76 | .46 |
| | Evaluating Arguments | 2 | 18.15 | 2.97 | .06 |
| Error | Critical Thinking Score | 91 | 79.21 | | |
| | Inference | 91 | 13.93 | | |
| | Recognizing Assumption | 91 | 10.13 | | |
| | Deduction | 91 | 13.17 | | |
| | Interpretation | 91 | 13.10 | | |
| | Evaluating Arguments | 91 | 6.11 | | |

Table 5.13 shows the homogeneity of regression slope of the high and low ability of the iSTEMa and traditional group in critical thinking subskills of inference, recognising assumption, deduction, interpretation, and evaluation of arguments. The result indicates there are no interaction effects between the students' ability group and critical thinking pre-test score.  The overall critical thinking skill results shows *F-ratio* for the interaction $F(2,91) = 1.38, p(.25) > .05$. Indicating that there are no statistical interaction effects. Therefore, in all the critical thinking subskills and the overall critical thinking score, we fail to reject the assumption for homogeneity of regression slope. It is indicating that there is no violation of the assumption of homogeneity of regression slope. Therefore, ANOVA was used to analyse the data.

### 5.5.4 Pre-test Comparison of High and Low Achievers of iSTEMa and Traditional Group Critical Thinking Skills

This is to determine the level of students' critical thinking status with regards to their academic ability level high, and low of the iSTEMa and traditional group. This is to circumvent any probable influence of students' academic ability to the critical thinking score after the intervention. Therefore, an analysis of variance (ANOVA) was used to determine the differences between the mean of the six groups in critical thinking skills pre-test score. The result is presented in Table 5.14

Table 5.14

*High, and Low Achievers' Pre-test Result of iSTEMa and Traditional Group Critical Thinking Skills.*

| Effect | | Value | F | Hypothesis df | Error df | Sig. |
|---|---|---|---|---|---|---|
| Groups | Pillai's Trace | .05 | 1.16 | 5.00 | 92.00 | .33 |
| | Wilks' Lambda | .94 | 1.16 | 5.00 | 92.00 | .33 |
| | Hotelling's Trace | .06 | 1.16 | 5.00 | 92.00 | .33 |
| | Roy's Largest Root | .06 | 1.16 | 5.00 | 92.00 | .33 |
| Ability | Pillai's Trace | .13 | 2.82 | 5.00 | 92.00 | .02 |
| | Wilks' Lambda | .86 | 2.82 | 5.00 | 92.00 | .02 |
| | Hotelling's Trace | .15 | 2.82 | 5.00 | 92.00 | .02 |
| | Roy's Largest Root | .15 | 2.82 | 5.00 | 92.00 | .02 |
| Groups * Ability | Pillai's Trace | .02 | .43 | 5.00 | 92.00 | .82 |
| | Wilks' Lambda | .97 | .43 | 5.00 | 92.00 | .82 |
| | Hotelling's Trace | .02 | .43 | 5.00 | 92.00 | .82 |
| | Roy's Largest Root | .02 | .43 | 5.00 | 92.00 | .82 |

Table 5.14 indicates the main effects of students' academic ability and the interaction effects between ability and the instructional approaches (iSTEMa and traditional group before treatment. There was a significant main effect of students' academic ability between the high and low achievers of the iSTEMa group and traditional group in the critical thinking subskills $F(5,92) = 2.82$, $p(0.02)$. The high ability students have a total mean of 39.88, which is higher than the total mean of the low ability students38.39 The significant difference is in favour of the high ability students.

There is no significant interaction effects between the independent variables (ability and instructional approach) $F(5, 92) = .43$, $p(.82) > 0.05$. Indicating that the instructional approaches did not interact with students' academic ability to enhance students' critical thinking score before the treatment. The result is further buttressed with the between-subjects effect for each critical thinking subskills or dependent variable. The result is as presented in Table 5.15.

*Table 5.15*

*Test of Between-subject effects on Pre-test Critical Thinking Skills*

| Source | Dependent Variable | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Groups | Inference | 1 | 18.67 | 2.61 | .10 |
| | Recognizing Assumption | 1 | 5.72 | 1.10 | .29 |
| | Deduction | 1 | 8.41 | 1.04 | .30 |
| | Interpretation | 1 | 3.82 | .53 | .46 |
| | Evaluating arguments | 1 | 1.20 | .28 | .59 |
| | Overall Score | 1 | 21.83 | .77 | .38 |
| Ability | Inference | 1 | 20.58 | 2.87 | .09 |
| | Recognizing Assumption | 1 | 5.76 | 1.10 | .29 |
| | Deduction | 1 | 11.26 | 1.40 | .23 |
| | Interpretation | 1 | 37.21 | 5.15 | .02 |
| | Evaluating arguments | 1 | 22.61 | 5.30 | .02 |
| | Overall Score | 1 | 52.90 | 1.86 | .17 |
| Groups * Ability | Inference | 1 | .80 | .11 | .73 |
| | Recognizing Assumption | 1 | 2.71 | .52 | .47 |
| | Deduction | 1 | .97 | .12 | .72 |
| | Interpretation | 1 | 3.19 | .44 | .50 |
| | Evaluating arguments | 1 | 4.39 | 1.03 | .31 |
| | Overall Score | 1 | 4.20 | .14 | .70 |
| Error | Inference | 96 | 7.15 | | |
| | Recognising Assumption | 96 | 5.20 | | |
| | Deduction pre | 96 | 8.03 | | |
| | Interpretation | 96 | 7.21 | | |
| | Evaluating arguments | 96 | 4.26 | | |
| | Overall Score | 96 | 28.35 | | |

The between-subject effects results in Table 5.15 indicates that, there was no significant difference between the Pre-test high and low achievers of iSTEMa and traditional group in inference, recognition of assumption and deduction critical thinking subskills; $F(1, 96) = 2.87$, $p = (.09) > 0.05$; $F(1, 96) = 1.10$, $p = (.29) > 0.05$; and $F(1, 96) = 1.40$, $p = (.23) > 0.05$ respectively. The result however, indicate a significant difference in interpretation and evaluation of arguments $F(1, 96) = 5.15$, $p = (.02) < 0.05$ and $F(1, 96) = 5.30$, $p = (.02) < 0.05$ respectively. The significant difference was in favour of high achievers. There were no significant interaction effects in all the critical thinking subskills as indicated in the factorial MANOVA result Table 5.12.

## 5.6 Pre-test Result of High and Low Ability in Genetic Achievement

Students' academic ability is an important moderating independent variable in this study; hence, the need to screen the genetic achievement data associated with it. The data screening of normality, homogeneity of variance, and homogeneity of regression slope as well as a test to determine the similarities of the iSTEMa and traditional group high and low achievers in genetic achievement score.

### 5.6.1 Normality Test

Normal distribution of the genetic achievement scores of high and low achievers of the iSTEMa and the traditional group was investigated to test the assumption of normality, and the result presented numerically. Kolmogorov-Smirnov test and Shapiro-Wilk Test was the numerical method employed. The result is as presented in Table 5.16.

Table 5.16

*Normality Test for Pre-test Genetic Achievement of High and Low Achievers of the iSTEMa and Traditional Group*

| Dependent Variable | Ability | Kolmogorov-Smirnov[a] Statistic | df | *P*-value | Shapiro-Wilk Statistic | Df | *P*-value |
|---|---|---|---|---|---|---|---|
| Genetic Achievement | iSTEMaHA | .14 | 20 | .20[*] | .91 | 20 | .06 |
| | iSTEMaLA | .13 | 31 | .13 | .96 | 31 | .44 |
| | *TradHA* | .15 | 19 | .20[*] | .96 | 19 | .70 |
| | *TradLA* | .11 | 30 | .20[*] | .96 | 30 | .30 |

*iSTEMa High Achievers (iSTEMaHA), iSTEMa Low Achievers (iSTEMaLA), traditional High Achievers (TradHA), and traditional Low Achievers (TradLA)*

Table 5.16 reveals the Kolmogorov-Smirnov and Shapiro Wilk's test result for iSTEMaHA was $F(20) = .14$, $p(.20) > .05$, and $F(20) = .91$, $p(.06) > .05$ respectively, showing that the data is normally distributed. The iSTEMaLA Kolmogorov-Smirnov test result shows $F(31) = .13$, $p(.13) > .05$, similarly, the Shapiro Wilk's test result of the iSTEMaLA in genetics was $F(31) = .96$, $p(.44) > .05$, showing that the data is normally distributed.

The *TradHA* Kolmogorov-Smirnov and Shapiro Wilk's test indicates that $F(19) = .15$, $p(.20) > .05$, and $F(19) = .96$, $p(.70) > .50$, which indicates that the data is approximately normally distributed. The *TradLA* Kolmogorov-Smirnov test indicates that $F(30) = .15$, $p(.20) > .05$, similarly, the Shapiro Wilk's test result of the *TradLA* indicates that $F$ (30) = .96, $p(.30) > .50$, which indicates that the data is approximately normally distributed. The result of the high and low achievers of the iSTEMa and the traditional group did not violate the assumption of normality. Therefore, the data is approximately normal. Hence, ANOVA was used to analyse the pre-test data (Piaw, 2013).

### 5.6.2 Levene's Test for Homogeneity of Variances for High and Low Achievers

The assumption of variance was checked using Levene's test for High, and low ability achievers for the pre-test iSTEMa and traditional group in genetic achievement score. The result is as presented in Table 5.17

Table 5.17

*Levene's Test for Homogeneity of Variances for Pre-test High and Low Achievers of iSTEMa and Traditional Group*

| | | Levene Statistic | df1 | df2 | *P*-value |
|---|---|---|---|---|---|
| Students' Ability | Terminology | 1.714 | 3 | 96 | .16 |
| | Mendel's laws | .430 | 3 | 96 | .73 |
| | Probability | 1.126 | 3 | 96 | .34 |
| | Overall | .621 | 3 | 96 | .60 |

Table5.17 present the result of Levene's test for homogeneity of variances for the pre-test scores of high and low achievers for iSTEMa and traditional group. The result indicates that there was no significant difference in the variances of the two groups in terminology, Mendel's laws and probability ($p$ >.05). The overall result indicates no significant variances between the groups $F(3, 96)$ =.621, $p$(.60) >0.05. It can be concluded that there are no differences among the variances of high and low achievers of the iSTEMa and traditional group. Therefore, the assumption for homogeneity of variance was not violated. The data was analysed using inferential statistics.

### 5.6.3 Pre-test Homogeneity of Regression Slope Students' Ability in Genetic achievement

The independent variables are the high, and low achiever of iSTEMa and traditional group, the dependent variable is the overall genetic score and the subscales scores of; genetic terminology, Mendel's laws and genetic probability for the post-test. While the covariates are the pre-test score. The results for homogeneity of regression slope for genetic achievement score for the high and low ability students of iSTEMa and the traditional group is as presented in Table 5.18

Table 5.18

*Homogeneity of Regression Slope of High and Low Students' Ability in Pre-test Genetic Achievement*

| Source | Dependent Variable | df | Mean Square | F | *P*-value |
|---|---|---|---|---|---|
| Intercept | Terminology | 1 | 4766.48 | 655.57 | .01 |
| | Mendel's Laws | 1 | 7498.21 | 393.84 | .01 |
| | Probability | 1 | 7183.15 | 722.98 | .01 |
| | Overall Score | 1 | 57785.16 | 1301.25 | .01 |
| Ability*Terminology *Mendel's laws *Probability * Overall | Terminology | 2 | 62.46 | 8.59 | .01 |
| | Mendel's Laws | 2 | 3.81 | .20 | .81 |
| | Probability | 2 | 11.25 | 1.13 | .32 |
| | Overall | 2 | 41.62 | .93 | .39 |
| Error | Terminology | 97 | 7.27 | | |
| | Mendel's Laws | 97 | 19.03 | | |
| | Probability | 97 | 9.93 | | |
| | Overall Score | 97 | 44.40 | | |

Table 5.18 shows the homogeneity of regression slope of students' ability groups in pre-test genetic achievement. The result of the terminology sub-dimension of genetics, $F(2, 97) = 8.59$, $p$ (.00) <.05, indicating that there is an interaction effect. Therefore, there was no violation of assumption for homogeneity of regression slope. Mendelian Laws sub-dimension of genetics achievement shows there is no interaction effects $F(2, 97) = .20$, $p(.32)$ >.05. Probability sub-dimension of genetics results indicates there is no interaction effects $F(6, 88) = .450$, p (.843) >.05. The overall genetic achievement results show $F(2, 97) = 1.13$, $p(.32)$ >.05, indicating that there are no statistical interaction effects.

Therefore, in Mendel's laws and probability sub-dimension as well as the overall genetic achievement, we fail to reject the hypothesis for the homogeneity of regression slope. This indicates that the assumption of homogeneity of regression slope of variance was not violated. However, the assumption was violated in genetic terminology. Therefore an examination of the standard deviation shows that the largest standard deviation was not four times greater than the smallest standard deviation, indicating ANOVA was robust in this case (Howell, 2007). ANOVA was used to analyse the results as planned because it is robust enough to accommodate this minor violation (Johnson, 2016). It is also essential to note that, the overall score of all the subsection did not violate the assumption.

### 5.6.4 Pre-test results of High and Low Ability Students of iSTEMa and Traditional Group

The achievement of students in genetics based on their GAT was determined using MANOVA because the dependent variables were more than two and the independent variable (ability) is more than two groups. The result is as displayed in Table 5.19

Table 5.19

*Comparison of Pre-test Genetic Achievement Based on Students' Ability*

| Effect | | Value | F | Hypothesis df | Error df | Sig. |
|---|---|---|---|---|---|---|
| Group | Pillai's Trace | .18 | 5.27 | 4.00 | 93.00 | .01 |
| | Wilks' Lambda | .81 | 5.27 | 4.00 | 93.00 | .01 |
| | Hotelling's Trace | .22 | 5.27 | 4.00 | 93.00 | .01 |
| | Roy's Largest Root | .22 | 5.27 | 4.00 | 93.00 | .01 |
| Ability | Pillai's Trace | .04 | 1.13 | 4.00 | 93.00 | .34 |
| | Wilks' Lambda | .95 | 1.13 | 4.00 | 93.00 | .34 |
| | Hotelling's Trace | .04 | 1.13 | 4.00 | 93.00 | .34 |
| | Roy's Largest Root | .04 | 1.13 | 4.00 | 93.00 | .34 |
| Group * Ability | Pillai's Trace | .06 | 1.53 | 4.00 | 93.00 | .19 |
| | Wilks' Lambda | .93 | 1.53 | 4.00 | 93.00 | .19 |
| | Hotelling's Trace | .06 | 1.53 | 4.00 | 93.00 | .19 |
| | Roy's Largest Root | .06 | 1.53 | 4.00 | 93.00 | .19 |

Table 5.19 indicates that there was no significant main effect of students' ability between the high and low achievers of the iSTEMa and traditional group in

genetic achievement; genetic terminology, Mendel’s laws and probability Wilks’ ʌ = .95, $F(4, 93) = 6.20$, $p = (.34) > 0.05$. Indicating that the high and low ability of iSTEMa and the traditional group were comparable before treatment. Similarly, there is no significant interaction effects between the two independent variables Wilks’ ʌ = .06, $F(4, 93) = 1.53$, $p = (.19) > 0.05$. The between-subjects effect for each dependent variable was presented to buttress the result as presented in Table5.20

Table 5.20

*Pre-test of Between-Subject Effects Students’ Ability on Genetic Achievement*

| Source | Dependent Variable | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Group | Terminology | 125.71 | 1 | 125.71 | 17.45 | .01 |
| | Mendel’s laws | 4.67 | 1 | 4.67 | .64 | .42 |
| | Probability | 3.25 | 1 | 3.25 | .62 | .43 |
| | Overall Score | 232.24 | 1 | 232.24 | 5.40 | .02 |
| Ability | Terminology | 19.23 | 1 | 19.23 | 2.67 | .10 |
| | Mendel’s laws | 7.91 | 1 | 7.91 | 1.08 | .30 |
| | Probability | 4.88 | 1 | 4.88 | .93 | .33 |
| | Overall Score | 56.53 | 1 | 56.53 | 1.31 | .25 |
| Group * Ability | Terminology | 6.83 | 1 | 6.83 | .94 | .33 |
| | Mendel’s laws | .86 | 1 | .86 | .11 | .73 |
| | Probability | 11.33 | 1 | 11.33 | 2.17 | .14 |
| | Overall Score | .24 | 1 | .24 | .00 | .94 |
| Error | Terminology | 691.25 | 96 | 7.20 | | |
| | Mendel’s laws | 699.78 | 96 | 7.28 | | |
| | Probability | 500.92 | 96 | 5.21 | | |
| | Overall Score | 4123.49 | 96 | 42.95 | | |

The between-subject effects results in Table 5.20 indicates that there was no significant difference between the high and low achievers of iSTEMa and traditional group in terminology, Mendel’s law Probability and the overall results. Similarly, there are no interaction effects between the independent variables in all dimension of genetic achievement.

## 5.7 Post-test Findings

To effectively determine the effect of integrated STEM approach intervention on critical thinking skill and students' genetic achievement, the Critical Thinking Test and Genetic Achievement Test (GAT)was administered as post-test for both the iSTEMa and traditional group after the intervention. The data collected from the post-test was scored base on the scoring procedures highlighted in the methodology and was subjected to analysis using the Statistical Package for Social Science (SPSS) Version 21.0. The results were presented based on the stated research questions and formulated hypotheses (Piaw, 2013). In the following sequence;

1. Data screening (normality distribution, homogeneity of variance, and homogeneity of regression slope)
2. Descriptive statistics
3. Inferential statistics

## 5.8 Post-Test Critical Thinking Skills Data Screening

To answer the research question which states that; Is there any significant mean difference in critical thinking skills between senior secondary school students that learn with iSTEMa (experimental group) and those who learn using the traditional method (control group)? First, the screening of data is done to determine the justification for the use of inferential statistics (ANCOVA). The validity of the result was based on the assumption that normality and the group variance must be equal or similar by yielding a p-value significance that is greater than .05 ($p > 0.05$).

### 5.8.1 Normality Test

Normal distribution of the critical thinking post-test scores of iSTEMa and the traditional group was investigated to test the assumption of normality, and the result presented numerically and graphically for each group. Kolmogorov-Smirnov test and Shapiro-Wilk Test was the numerical method employed. The result is presented in Table 5.21

Table 5.21

*Kolmogorov-Smirnov Test and Shapiro-Wilk Test for iSTEMa and Traditional Group Critical Thinking Post-test Scores*

| | Groups | Kolmogorov-Smirnov[a] | | | Shapiro-Wilk | | |
|---|---|---|---|---|---|---|---|
| | | Statistic | Df | Sig. | Statistic | df | *P-value* |
| CTS Score | iSTEMa | .11 | 51 | .169 | .97 | 51 | .21 |
| | Traditional | .10 | 49 | .200* | .98 | 49 | .55 |

*This is a lower bound of the true significance. a. Lilliefors Significance Correction

Table 5.21 indicates that Kolmogorov-Smirnov test for iSTEMa group post-test was *F*(51) =.110, *p* (.169) >.05, While the Shapiro-Wilk test *F*(51) =.97, *P*(.21) >.05. The traditional group Kolmogorov-Smirnov test *F*(49) =.107, *p*(.20) >.05, while the Shapiro-Wilk test *F*(49) =.98, *P*(.55) >.05. Consequently, the results indicate that the *p-value* of the two tests, for the two groups (iSTEMa and traditional group) was greater than 0.05. *(p*>0.05). Therefore, the data is said to be approximately normal. The result is further presented in the form of the histogram to highlight normal distribution. The histogram of iSTEMa and the traditional group is as presented in Figure 5.5 and 5.6

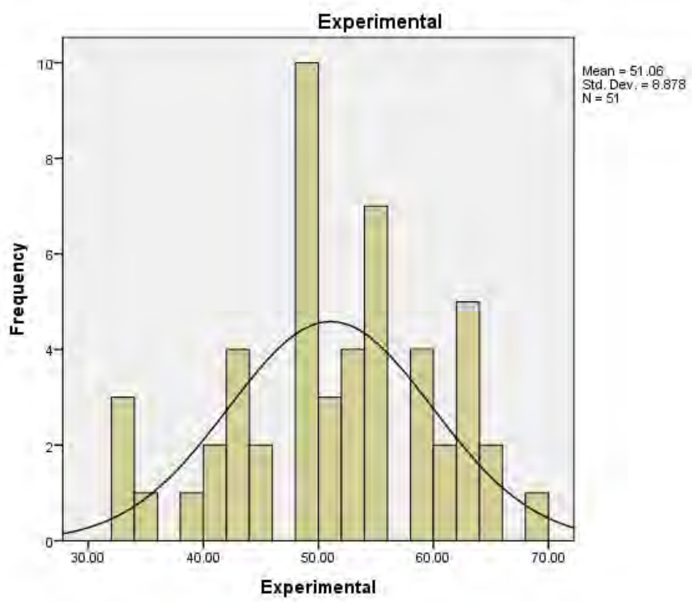


*Figure 5.5* Histogram for Experimental Group Post-test Critical Thinking Skills

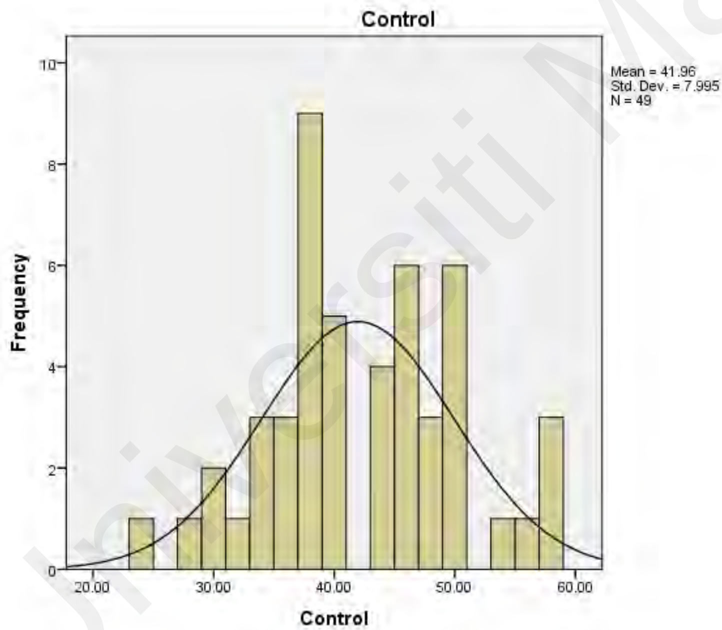


*Figure 5.6* Histogram for Traditional Group Post-test Critical Thinking Skills Score

Figure 5.5 and 5.6 shows the visual histogram post-test output of the iSTEMa and traditional group normality respectively, the visible histogram output has a relatively accurate shape of a normal curve based on the Kolmogorov-Smirnov test and Shapiro-Wilk output. Therefore, it is assumed that the critical thinking skills post-test data of the two groups (iSTEMa and traditional group) are approximately normally distributed. The data were analysed using MANOVA.

### 5.8.2 Homogeneity of Variance

Homogeneity of variance assumption was scrutinise using Levene's test. This test determines whether the variances of the variables are significantly different (Warner, 2013). The analysis of homogeneity of variance of critical thinking skill data of the iSTEMa and traditional group is as presented in Table 5.22

Table 5.22

*Test of Homogeneity of Variances for Post-test Critical Thinking Sub-skills between Experimental and Control*

| | Levene Statistic | df1 | df2 | *P-value* |
|---|---|---|---|---|
| Inference | .42 | 1 | 98 | .51 |
| Recognition of Assumption | 5.99 | 1 | 98 | .01 |
| Deduction | .09 | 1 | 98 | .76 |
| Interpretation | .85 | 1 | 98 | .35 |
| Evaluating Arguments | 1.70 | 1 | 98 | .19 |
| Overall Score | .54 | 1 | 98 | .46 |

Table 5.22 clearly shows that the subscale inference $F(1,98) = .42$, p(.51) >.05 deduction $F(1,98) = .09$, p(.76) >.05, interpretation $F(1,98) = .85$, $p(.35) > .05$, evaluating arguments $F(1,98) = 1.70$, p(.19) >.05, which did not violates the assumption of homogeneity of variances. While recognition of assumption was $F(1, 98) = 5.99$, p (.01) <.05 violates the assumption, however, the ANCOVA analysis is robust to accommodate this slight violation and the result will not be significantly affected (Johnson, 2016). The researchers will also adopt Pillar's trace to interpret the results because it is more robust to accommodate slight violations of assumptions (Giri & Datt, 2017).

However, the overall post-test result of the iSTEMa and traditional groups was $F$ (1, 98) = .54, p (.46) >.05, which did not violate the assumption of homogeneity of variance. It is, therefore, concluded that the iSTEMa and traditional group variance was approximately homogeneous for critical thinking skill post-test results. Consequently, the analysis will proceed as plan.

### 5.8.3 Homogeneity of Regression Slope for Post-test Critical Thinking Skills of iSTEMa and Traditional Group

Homogeneity of the regression slope determines whether the independent variables have parallel regression slope, indicating that there is a similar covariate slope for the two groups. If the result yields interaction effects, then the assumption for the use of ANCOVA is violated. The independent variables are the iSTEMa and traditional group. The dependent variable is the post-test of critical thinking skill score. While the covariates are the pre-test score of critical thinking skills. The results for homogeneity of regression slope for critical thinking skill score for the iSTEMa and traditional group is as presented in Table 5.23

Table 5.23

*Homogeneity of Regression Slope of iSTEMa and Traditional Group in Critical Thinking Skills Post-test*

| Source | Dependent Variable | Df | Mean Square | F | *P*-value |
|---|---|---|---|---|---|
| Intercept | Inference | 1 | 2086.45 | 282.73 | .01 |
| | Recognizing Assumption | 1 | 3144.04 | 603.24 | .01 |
| | Deduction | 1 | 4242.49 | 519.52 | .01 |
| | Interpretation | 1 | 2383.37 | 317.57 | .01 |
| | Evaluating arguments | 1 | 4703.61 | 1052.26 | .01 |
| | Overall | 1 | 80818.88 | 2826.90 | .01 |
| Groups * Inference * Recognizing Assumption * Deduction * Interpretation * Evaluating Arguments * Overall | Inference | 2 | 6.71 | .91 | .40 |
| | Recognizing Assumption | 2 | 3.64 | .69 | .50 |
| | Deduction | 2 | .76 | .09 | .91 |
| | Interpretation | 2 | 5.51 | .73 | .48 |
| | Evaluating arguments | 2 | 2.30 | .51 | .59 |
| | Overall | 2 | 11.88 | .41 | .66 |
| Error | Inference | 97 | 7.37 | | |
| | Recognizing Assumption | 97 | 5.21 | | |
| | Deduction | 97 | 8.16 | | |
| | Interpretation | 97 | 7.50 | | |
| | Evaluating arguments | 97 | 4.47 | | |
| | Overall | 97 | 28.58 | | |

Table5.23 shows the post-test homogeneity of regression slope of iSTEMa and traditional group (independent variable) on critical thinking subskills of inference, recognising assumption, deduction, interpretation, and evaluation of arguments post-test score (dependent variable). The result indicates there are no interaction effects between the iSTEMa and traditional group in all the subdimensions of critical thinking skills (*p*>.05). The overall critical thinking skill results shows $F(2,97) = .41, p(.66) > .05$. Indicating that there are no statistical interaction effects. Therefore, in all the critical thinking subskills and the overall critical thinking score, we fail to reject the hypothesis for the assumption for homogeneity of regression slope. It is indicating that the assumption of homogeneity of regression slope of variance was not violated.

## 5.9 Descriptive Statistics of Pre-test and Post-test Critical Thinking Skill

To answer research question one, descriptive statistics were employed firstly to determine the mean differences between integrated STEM approach and the traditional teaching method in enhancing critical thinking skills. The data obtained were analysed to compare the mean and standard deviation of the iSTEMa and traditional group in the five subscales of critical thinking skill (inference, recognition of assumption, deduction, interpretation, and evaluation of arguments). The result is as presented in Table 5.24

Table 5.24

*Means and Standard Deviation Comparison of Pre-test and Post-test Result for Critical Thinking Skill of iSTEMa and Traditional Group*

| Critical Thinking Skills | Group | Pre-test | | Post-test | | Mean Gain | Mean Gain Difference |
|---|---|---|---|---|---|---|---|
| | | Mean | SD | Mean | SD | | |
| Inference | iSTEMa | 5.80 | 2.53 | 9.76 | 3.60 | 3.93 | 3.09 |
| | Traditional | 6.73 | 2.40 | 7.57 | 3.39 | 0.84 | |
| Recognizing Assumption | iSTEMa | 7.25 | 2.34 | 9.63 | 3.70 | 2.38 | 1.99 |
| | Traditional | 7.67 | 2.20 | 8.51 | 2.42 | 0.84 | |
| Deduction | iSTEMa | 9.25 | 3.10 | 11.08 | 3.54 | 1.83 | 1.62 |
| | Traditional | 8.61 | 2.98 | 8.82 | 3.59 | 0.21 | |
| Interpretation | iSTEMa | 6.67 | 2.54 | 9.76 | 3.63 | 3.09 | 2.45 |
| | Traditional | 7.14 | 2.92 | 7.78 | 3.71 | 0.64 | |
| Evaluating Argument | iSTEMa | 9.57 | 2.50 | 10.82 | 2.86 | 1.25 | 1.20 |
| | Traditional | 9.24 | 1.58 | 9.29 | 2.41 | 0.05 | |
| Overall | iSTEMa | 38.53 | 5.69 | 51.06 | 8.87 | 12.53 | 9.98 |
| | Traditional | 39.41 | 4.91 | 41.96 | 7.99 | 2.55 | |

Table 5.24 displays the mean, standard deviation and mean gain of iSTEMa and traditional group in critical thinking skill dimension of inference, recognition of assumption, deduction, interpretation, and evaluation of arguments. The result shows

an improvement of critical thinking skills from pre-test – post-test in all dimension of critical thinking skills, showing that the students gained from the treatment.

The result in the inference dimension, the iSTEMa group pre-test means (5.80) and the post-test mean was (9.76) the mean gained was (3.93). On the other hand, the traditional group pre-test mean was (6.73) and the post-test was (7.57), the mean gained was (0.84). Thus, the mean gain difference between the iSTEMa and traditional group was (3.09) in favour of the iSTEMa group. Indicating that the iSTEMa enhanced inference subskill of critical thinking skills of the iSTEMa group than the traditional instructional method

The result in recognition of assumption subskill, the iSTEMa group pre-test mean (7.25) and the post-test mean (9.63) the mean gained was (2.38). On the other hand, the traditional group pre-test mean was (7.67) and the post-test was (8.51), the mean gained was (0.84). Thus, the mean gain difference between the iSTEMa and traditional group was (1.99) in favour of the iSTEMa group.

In deduction subskill, the iSTEMa group pre-test mean (9.25) and the post-test mean (11.08) the mean gained was (1.83). On the other hand, the traditional group pre-test mean was (8.61) and the post-test was (8.82), the mean gained was (0.21). Thus, the mean gain difference between the iSTEMa and traditional group was (1.62) in favour of the iSTEMa group. It is indicating that the iSTEMa more effective than the traditional method in enhancing deductive skills.

The result of the subskill of interpretation shows that the iSTEMa group pre-test means (6.67) and the post-test mean (9.76) the mean gained was (3.09). On the other hand, the traditional group pre-test mean was (7.14) and the post-test was (7.78), the mean gained was (0.64). Consequently, the mean gain difference between the iSTEMa and traditional group was (2.45) in favour of the iSTEMa group. Indicating that the iSTEMa enhanced interpretation subskill of critical thinking skills of the iSTEMa group that the traditional instructional method

In evaluating arguments subskill, the iSTEMa group pre-test means (9.57) and the post-test mean was (10.82) the mean gained was (1.22). On the other hand, the traditional group pre-test mean was (9.24) and the post-test mean (9.29), the mean gained was (0.05). Thus, the mean gain difference between the iSTEMa and traditional group was (1.20) in favour of the iSTEMa group.

The overall critical thinking skills show that the iSTEMa group pre-test means (38.55) and the post-test mean (51.06) the mean gained was (13.53). On the other hand, the traditional group pre-test mean was (39.41) and the post-test mean was (41.96), the mean gained was (2.55). Thus, the mean gain difference between the iSTEMa and traditional group was (9.98) in favour of the group that learns with iSTEMim. Indicating that the iSTEMa enhanced overall critical thinking skills of the iSTEMa group that the traditional instructional method did for the control. This is highlighted graphically in Figure 5.7

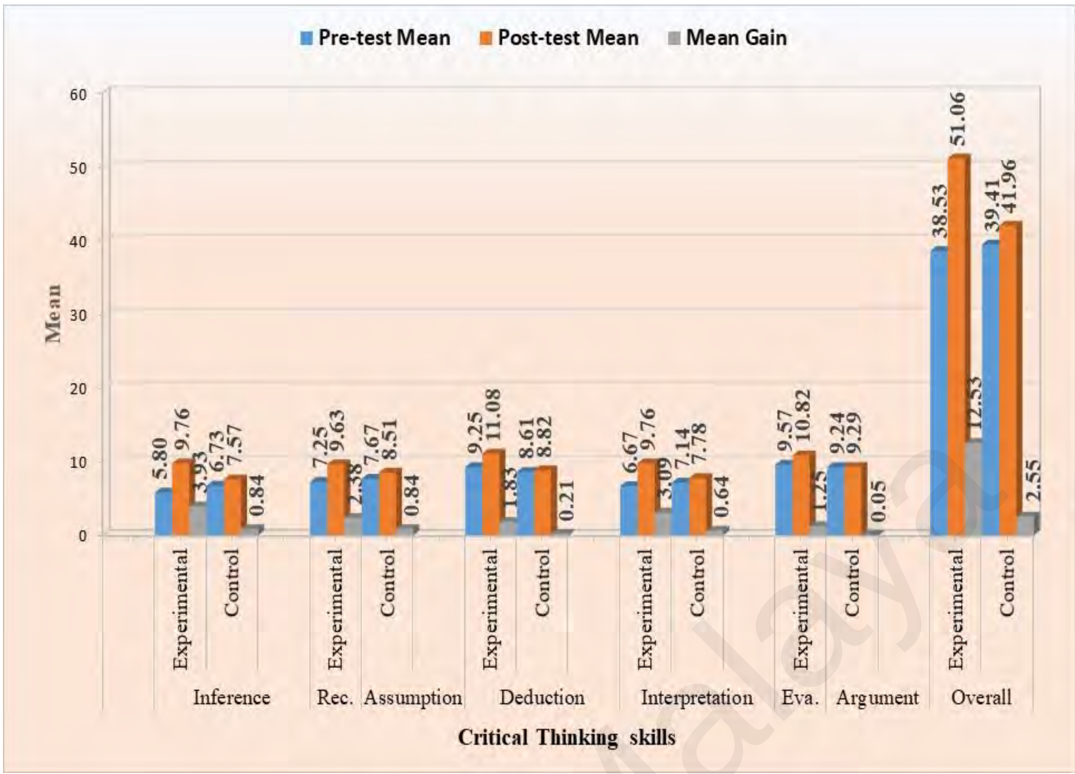


*Figure 5.7. Pre-test and Post-test Mean comparison of iSTEMa and Traditional Group in Critical Thinking Skills*

Figure 5.7 shows the means of the iSTEMa and traditional group as well as the mean difference between the two groups. The iSTEMa group performed better than the traditional group in all the sub-dimension of critical thinking skills (inference, recognition of assumption, deduction, interpretation, and evaluation of arguments). This could be attributed to the effects of integrated STEM approach. The result was subjected to further analysis of within-group comparison using a dependent t-test and effects size.

## 5.10 The Within-Group Comparison of Critical Thinking Skills

To test for research hypothesis one, (There is no significant difference in the critical thinking skills between selected senior secondary school students that learn with iSTEMa and those who learn using the traditional method).

The researcher first compares the means of within-group, that is between the pre-test and post-test to determine the effects of treatment, followed by determining the effect size of the difference for both the iSTEMa and traditional group. A dependent t-test was employed to ascertain whether each group improves or not and the result is as presented in Table 5.25

Table 5.25

*Within-group Comparison of Critical Thinking Skills Score*

| **Ability** | **Group** | **Pre-test mean ± SD** | **Post-test mean ± SD** | ***df*** | ***t-value*** | ***p-value*** | ***d²*** | |
|---|---|---|---|---|---|---|---|---|
| Inference | iSTEMa | 5.80±2.53 | 9.76±3.60 | 50 | -6.14 | .01 | 1.27 | large |
| | Traditional | 6.73±2.84 | 7.57±3.39 | 48 | -1.39 | .17 | .26 | small |
| Recognising Assumption | iSTEMa | 7.25±2.34 | 9.63±3.70 | 50 | -3.98 | .01 | .76 | medium |
| | Traditional | 7.67±2.20 | 8.51±2.24 | 48 | -1.73 | .09 | .38 | small |
| Deduction | iSTEMa | 9.25±3.10 | 11.08±3.45 | 50 | -2.73 | .01 | .55 | medium |
| | Traditional | 8.61±2.50 | 8.82±3.59 | 48 | -2.91 | .34 | .06 | small |
| Interpretation | iSTEMa | 6.67±2.54 | 9.76±3.58 | 50 | -5.15 | .01 | .99 | large |
| | Traditional | 7.14±2.92 | 7.78±3.71 | 48 | -.95 | .33 | .19 | Small |
| Evaluation | iSTEMa | 9.570±2.50 | 10.82±2.86 | 50 | -2.50 | .02 | .50 | Medium |
| | Traditional | 9.24±1.58 | 9.29±2.54 | 48 | -.10 | .91 | .25 | Small |
| Overall | iSTEMa | 38.55±5.69 | 51.06±8.87 | 50 | -9.11 | .01 | 1.67 | Large |
| | Traditional | 39.41±4.91 | 41.96±7.99 | 48 | -1.92 | .60 | .38 | Small |

Table 5.25 reveals a significant mean difference can be observed between the pre-test and the post-test mean scores of the iSTEMa in all the subskills of critical

thinking skills of the iSTEMa group; inference $t(50) = -6.14$, $p(.01) <.05$; $d^2=1.27$; recognising assumption $t(50) = --3.98$, $p(.00) <.05$, $d^2=76$; deduction $t(50) = -2.73$, $p(.00) <.05$, $d^2=55$; interpretation $t(50) = -5.15$, $p(.00) <.05$, $d^2=99$; and evaluation $t(50) = -2.50$, $p(.01) <.05$, $d^2=50$. The effect sizes were large, medium, medium, large, medium and large respectively. On the other hand, there is no significant mean difference in all the critical thinking subskill of the traditional group; inference subskill $t(48) = -1.39$, $p(.17) >.05$, $d^2=26$; recognising assumption $t(48) = -1.73$, $p(.09) >.05$, $d^2=38$; deduction $t(48) = -2.91$, $p(.34) >.05$, $d^2=.06$; interpretation $t(48) = -.95$, $p(.33) >.05$, $d^2=.19$; and evaluation $t(48) = -.10$, $p(.91) >.05$, $d^2=25$. The effect sizes were all small respectively.

Accordingly, there was a significant mean difference between the pre-test and post-test in the overall critical thinking skills of the iSTEMa group $t(50) = -9.11$, $p(.01) <.05$, the overall effect size of iSTEMa group ($d^2=1.67$) indicating large effect size. This indicates that iSTEMa has a large effect size in enhancing students' critical thinking skills of the iSTEMa group. On the contrary, there was no significant mean difference between the pre-test and post-test in the overall critical thinking skills of the traditional group $t(48) = -1.92$, $p(.60) >.05$, the overall effect size of the traditional group ($d^2=0.38$), indicating small effect size. The $p$-value shows clearly whether there is a significant difference or not but will not reveal the size or magnitude of the difference (Sullivan & Feinn, 2012). Therefore, in comparison, the iSTEMa had a large effect in enhancing students' critical thinking skills while the traditional method had a small effect size in helping students to think critically.

## 5.11 The between Group Comparison in Critical Thinking Skills

To determine the effects of treatment between the iSTEMa and traditional group (students treated with integrated STEM approach and a traditional instructional method respectively), among the selected secondary school students. Since the pre-test between the two groups was not significant, Multivariate Analysis of Variance (MANOVA) was used to analyse the critical thinking skills data between the iSTEMa and traditional group. Pillar's Trace was used to interpret the MANOVA results. The researchers adopted the Pillar's trace because it is more robust to accommodate slight violations of assumptions (Giri & Datt, 2017). The analysis is as presented in Table 5.26

Table 5.26

*Post-test MANOVA Result of Critical Thinking Subskills for iSTEMa and Traditional group*

| Effect | | Value | F | Hypothesis df | Error df | *P*-value | Partial $\eta^2$ |
|---|---|---|---|---|---|---|---|
| Intercept | Pillai's Trace | .97 | 623.67 | 5.00 | 94.00 | .01 | .97 |
| | Wilks' Lambda | .02 | 623.67 | 5.00 | 94.00 | .01 | .97 |
| | Hotelling's Trace | 33.17 | 623.67 | 5.00 | 94.00 | .01 | .97 |
| | Roy's Largest Root | 33.17 | 623.67 | 5.00 | 94.00 | .01 | .97 |
| Groups | Pillai's Trace | .23 | 5.88 | 5.00 | 94.00 | .01 | .24 |
| | Wilks' Lambda | .76 | 5.88 | 5.00 | 94.00 | .01 | .24 |
| | Hotelling's Trace | .31 | 5.88 | 5.00 | 94.00 | .01 | .24 |
| | Roy's Largest Root | .31 | 5.88 | 5.00 | 94.00 | .01 | .24 |

Table 5.26 shows MANOVA results, comparing the post-test scores of iSTEMa and traditional group in critical thinking skills after the treatment, using Pillai's Trace test at 0.05 alpha level. The result shows that there is significant difference between the iSTEMa (group that learned using iSTEMim) and the traditional group (traditional method) in critical thinking skills, Pillai's Trace $\wedge$ = .23, $F(5,94) = 5.88$, $p= (0.01) < 0.05$, partial $\eta^2 = .24$. This indicates a significant difference between the iSTEMa and traditional group. The multivariate partial $n^2$ (.238) shows

that about 24% of the total variances in critical thinking skills can be attributed to the independent variables (instructional approaches).

Since the results were significant, we need to look at the between-subjects effect or univariate tests for each dependent variable. The result is as presented in Table 5.27.

Table 5.27

*Test of Between-subjects effect*

| Source | Dependent Variable | df | Mean Square | F | *P*-value | Partial $\eta^2$ |
|---|---|---|---|---|---|---|
| Intercept | Inference | 1 | 7510.53 | 610.72 | .01 | .862 |
| | Recognition of Assumption | 1 | 8221.07 | 832.15 | .01 | .895 |
| | Deduction | 1 | 9891.07 | 796.46 | .01 | .890 |
| | Interpretation | 1 | 7688.40 | 578.82 | .01 | .855 |
| | Evaluating Arguments | 1 | 10105.49 | 1432.34 | .01 | .936 |
| | Overall Score | 1 | 216222.21 | 3023.33 | .01 | .969 |
| Groups | Inference | 1 | 120.21 | 9.77 | .01 | .091 |
| | Recognition of Assumption | 1 | 31.19 | 3.15 | .07 | .031 |
| | Deduction | 1 | 127.87 | 10.29 | .01 | .095 |
| | Interpretation | 1 | 98.88 | 7.44 | .01 | .071 |
| | Evaluating Arguments | 1 | 59.09 | 8.37 | .01 | .079 |
| | Overall Score | 1 | 2069.25 | 28.93 | .01 | .228 |
| Error | Inference | 98 | 12.29 | | | |
| | Recognition of Assumption | 98 | 9.87 | | | |
| | Deduction | 98 | 12.41 | | | |
| | Interpretation | 98 | 13.28 | | | |
| | Evaluating Arguments | 98 | 7.05 | | | |
| | Overall Score | 98 | 71.51 | | | |

The univariate test in Table 5.27 shows that, there was a significant difference between the post-test scores of iSTEMa and traditional group in the critical thinking subskill of inference $F$ (1, 98) = 9.77, $p$ = (.00) < 0.05, partial $\eta^2$ = 0.91 indicates that approximately 9.1% of the variance in inference subskill is due to treatment. The iSTEMa group estimated mean 9.78 is higher than the mean of the traditional group 7.55; therefore, the significant difference was in favour of the iSTEMa group.

There was no significant difference between the iSTEMa and traditional group in recognition of assumption $F(1, 98) = 3.15$, $p = (0.07) > 0.05$, partial $\eta^2 = 0.031$. The $\eta^2$ indicated that approximately 3.1% of the variance in recognition of assumption could be explained by treatment. The iSTEMa group estimated mean 9.62 which is higher compared to the estimated mean of the traditional group 8.52. Therefore, the iSTEMa was more effective in enhancing the recognition of assumption more than the traditional method.

There was a significant difference between the iSTEMa and traditional group in deduction $F$ (1, 98) = 10.29, $p = (0.01) < 0.05$, partial $\eta^2 = 0.095$. The $\eta^2$ indicated that approximately 9.5% of the variance in deduction subskill is due to treatment. The iSTEMa group estimated mean 11.09 was higher than the estimated mean of the traditional group 8.81. Consequently, the significant difference is in favour of the iSTEMa group.

The result of critical thinking subskill of interpretation was $F$ (1, 98) = 7.44, $p = (0.01) < 0.05$, partial $\eta^2 = 0.071$. This indicates a significant difference between the iSTEMa and traditional group. The $\eta^2$ (0.071) indicated that approximately 7.1% of the total variance in interpretation is due to the independent variables. The iSTEMa group estimated mean 9.76 which is higher compared to the estimated mean of the traditional group 7.78; therefore, the significant difference was in favour of the iSTEMa group.

There was no significant difference between the iSTEMa and traditional group in evaluating arguments $F$ (1, 98) = 8.37, p = (0.01) < 0.05, partial n2 = 0.079. The $\eta^2$ indicated that approximately 7.9% of the variance in evaluating arguments subskill was due to treatment. The iSTEMa group estimated mean 10.84 which is higher compared to the estimated mean of the traditional group 9.26. Therefore, the significant difference was in favour of the iSTEMa group.

The overall effect of treatment between the iSTEMa and traditional group in the overall critical thinking skills were $F$ (1, 98) = 28.93, p = (.01) < 0.05, partial $n^2$ = .228. This indicates a significant difference between the means of iSTEMa and traditional group. The $\eta^2$ (.228) showed that approximately 22.8% of the variance in the overall critical thinking skills was due to the effects of the instructional approaches. The iSTEMa group estimated mean 51.12 which is higher compared to the estimated mean of the traditional group 41.89, the significant difference was in favour of the iSTEMa group. Therefore, the formulated hypothesis which states that there is no significant difference in the critical thinking skills between selected senior secondary school students that learn with iSTEMa and those who learn using the traditional method is rejected. The overall critical thinking estimated means could be highlighted as presented in Figure 5.8

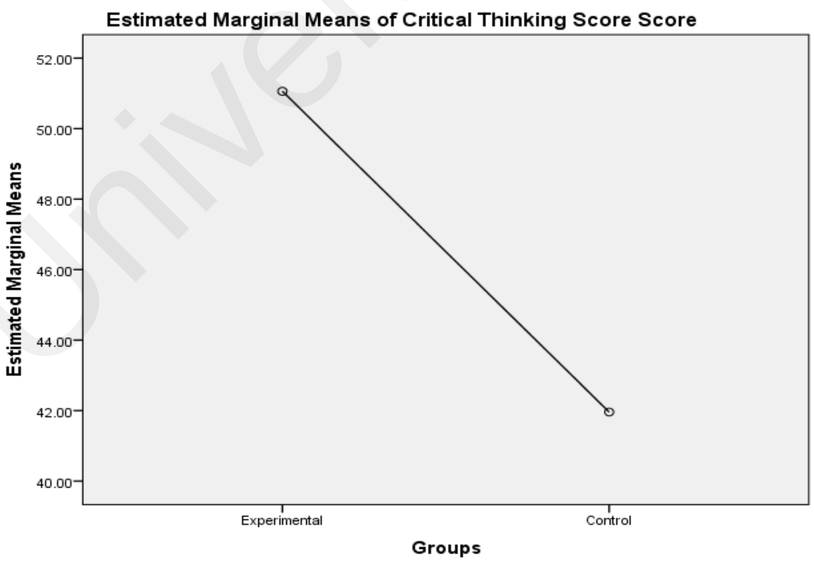


*Figure 5.8* Estimated Marginal Means of iSTEMa (Experimental) and Traditional Group (Control) Critical Thinking Score

Figure 5.8, the overall estimated marginal means of iSTEMa and traditional group critical thinking score indicates that the integrated STEM approach was more effective in enhancing critical thinking skills than the traditional group among secondary school students. The findings agree with the earlier findings of researchers which reported that instructional approach characterised by the open-ended problem, generation of ideas and teamwork significantly influence the development of critical thinking skills (Carvalho et al., 2015; Lay & Osman, 2017).

### 5.12 How iSTEMa Enhanced Critical Thinking Skills

Given the finding of the quantitative above, to answer the research question (1b); how does the iSTEMa enhance critical thinking skills among senior secondary school students? Data from verbal and nonverbal data were used to identify the key elements that could have promoted cognitive processes and the mental processes that students engage leading to the improvement of students' critical thinking skills among the sample of the population.

The qualitative findings suggest that students appear to be actively engaged in cognitive learning processes using iSTEMa. The students were observed to be working individually as well as in a group. Observation and interview data suggest that students were involved in activities that promote higher cognitive activities. They were also engaged in sketching their ideas and group projects, which could have enhanced students' ability to think critically. Therefore, qualitative data is group into two themes that could have helped to enhance students' critical thinking skills. The two themes were instructional scaffolds and promotion of cognitive processes.

### 5.12.1 Instructional Scaffold

The theme instructional scaffold provides support and independence for the students to stay within the boundaries of the instructional process and activities. This seems to suggest that the organisation of instructional material (iSTEMim) that was developed to implement iSTEMa help promote higher cognitive processes through supported tasks. Students' individual learning experiences and group interaction seem to suggest that the iSTEMa provided support or scaffold (support provided for learners during the instructional process) for cognitive processes. Students were involved in learning activities such as hands-on activities, defining problem, searching for relevant ideas and information, sketching among others. Students non-verbal behaviours and verbal statements or accounts mirror the approach providing scaffolds which may have enhanced critical thinking skills among the participants.

Three scaffolding techniques or subthemes were identified from the data: instructional sequence, learning clues and probing questions. Each of these sub-themes was defined based on the nature of the scaffold provided as highlighted in Table 5.28

Table 5.28

*Instructional Scaffold Sub-themes and their Definitions*

| **Category/Sub-theme** | **Definition** |
|---|---|
| Instructional Sequence | The sequential or logical arrangement of the integrated STEM approach learning phases. |
| Learning Clues | These are instructional guides provided to enhance the students learning and cognitive engagement |
| Probing Question | These are open-ended questions that engage or provoke learners' critical thinking skills |

a Instructional Sequence

The iSTEMa instructional material (iSTEMim) was structure to be student-centred. Therefore, it provided some procedure or sequence of phases which serve as a scaffold for students' learning.

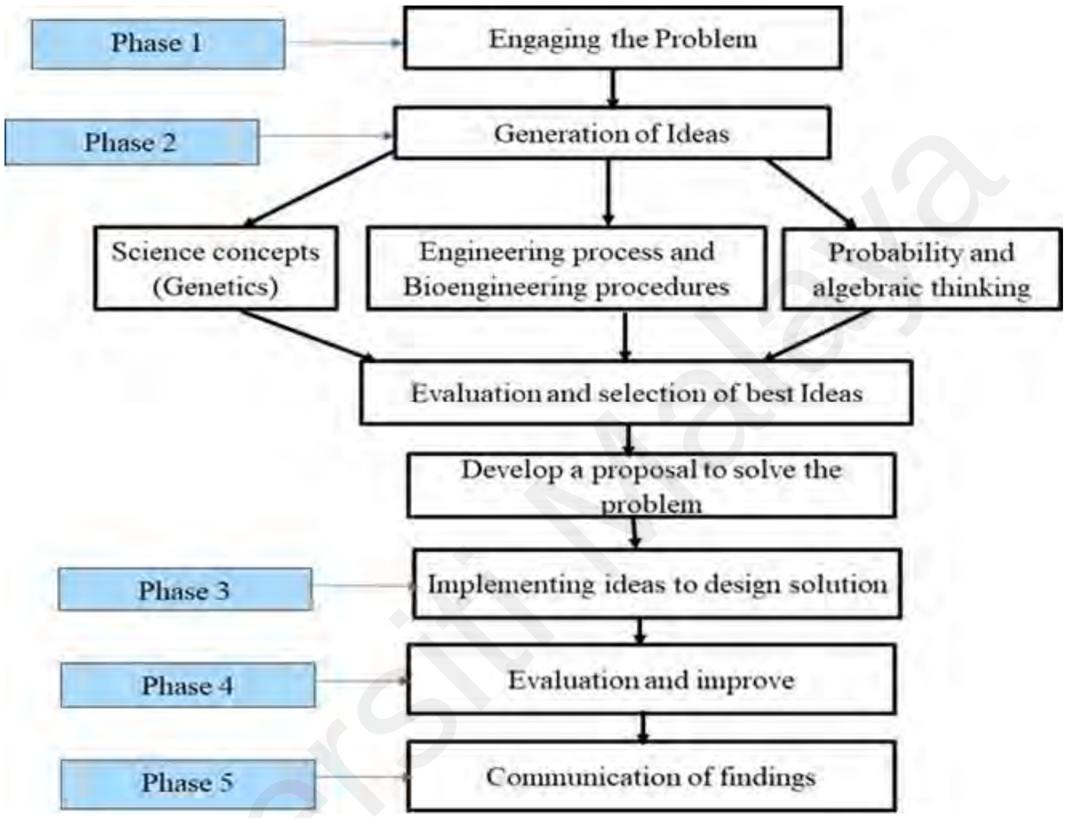


*Figure 5.9. iSTEMa Instructional Sequence*

Although the phases are arranged logically, the students have the liberty to move forth and back to earlier stages thus providing opportunities for reflective thinking which may have enhanced critical thinking skills. Students verbal data indicates that the sequence of the approach seems to support and improve students' critical thinking skills as indicated in the excerpts below

> *Each stage serves as a link to the next one. Umm... for example, we began by writing what we know about the problem and what do we need to know about the problem. Therefore, during the generation of ideas, I refer to what I need*

*to know about the problem (reflection) which was genetic laws and principles as well as procedures for genetic engineering*

*(Ezenwa, Interview, 24th/03 2017)*

*In the beginning, I was able to link problem scenario to what I already know (genetically modified organism), which encourage me to think more about the problem scenario unlike the regular classes we listen and write*

*(Sheri, Interview, 23rd/03 2017)*

The students seem to navigate the learning sequence with little or no difficulties, and the approach seems to provide support for learners to think out of the box because their several ways and solution to the problem thus encouraging them to think as indicated in the students' excerpts presented below

*Um.. to me the organisation of the approach (STEM) influenced everyone to be curious about finding a solution to a problem that will benefit society. There are several ways to address the problem, but working through the phases and sometimes we refer to the previous phases especially the first phase where the goal of the problem is established*

*(Aisha, Interview, 24/03/2017)*

*The arrangement of the approach allows everyone to think and articulate his ideas first before meeting in a group to share, and defend his ideas which motivate me, and others to contribute to the learning process*

*(Bege, Interview, 24/03/2017)*

*the approach offers us the opportunity and freedom to learn and solve the problem on our own by providing the task in (….) stages [phases] which were helpful. We found information individually and met to discuss our ideas as a group at the end of each phase*

*(Dami, Interview, 23/03/2017)*

The phases of the iSTEMa appear to scaffold students' learning by creating a self-directed and user-friendly environment that allows students to work on their own as indicated in the following students' excerpts below:

*In this approach, we [students]carry out the activities ourselves with ease because of the stages, um … moving from one stage to the other bearing in mind the goal of the problem, the teacher comes in when we are stuck*

*(Ezenwa, Interview, 24/03/2017)*

*In general, the approach helps me keep track of my learning, and I enjoy the exercises more than in our normal classes*

*(Hameed Interview, 23/03/2017)*

*The organisation of the approach which allow us [students] to participate more [actively engage] in looking for different information on genetics and probability as well as bioengineering*

*(Aisha, Interview, 24/03/2017)*

Observation of students' classroom activities indicated that students follow the instructional phases effectively. During the generation of ideas, students were observed engaging in simulation to demonstrate how traits are inherited from parents by offspring as indicated in this excerpts

*Group one (1) was observed simulating Mendel's inheritance of gender in man using two coins which represent the father and the mother's alleles (Observation, 1st/02/2017)*

Learners were observed always referring to the goal of the problem thus moving forth and back the instructional phases and were working at a different speed;

*The students were observed doing different things at the same time, for example, some searching for information in their textbooks while others on the internet at the same time some were having a group discussion*

*(Observation,23rd/02/2017)*

*The instructional phases which adopted the engineering design process, learners were observed working individually on each phase before meeting as a group to interrelate*

*(Observation,23rd/02/2017)*

The logical arrangement of the instructional approach seems to have enhanced students' centred learning and engagement which could have enhanced students' critical thinking skills. Based on the findings on instructional sequence it could be inferred that the qualitative findings seem to triangulate the quantitative data that showed the iSTEMa group perform better than the traditional group b **Learning Clues**

Thinking does not take place in a vacuum or automatically but must be stimulated. The data seem to suggest students engaging in the use of appropriate evidence, scenario, problems, and puzzles which are embedded in the approach. These elements (open-ended problem and guides) are categorised under this sub-theme. In this study, the problem scenario was presented, and the process of studying the problem and considering the different perspective on the problem involves cognitive activities like analysis, evaluation, and interpretation. Therefore, the nature of the problem seems to provide a clue that engages learners' cognitive abilities. The open-ended problem;

> *A sale representative specialises in marketing the African savanna wild rabbit called the Hare which has an estimated length between 41 – 58 cm and the weight between 1.5 – 3 kilograms (kg). This animal is threatened by extinction, and your group is contacted by a sales representative (marketer) to engineer a unique Hare that is of value and solve a problem in the society that could attract investment.*

In the problem, the term "Unique Hare" and "of Value" makes the problem open-ended because what may be unique to one person may not be unique to the other. The students are expected to speculate what is their unique animal and justify why they think the proposed animal will be unique. Furthermore, the learners could address various problems in the society. This agrees with Cox et al. (2016b) who observed that an open-ended problem or ill-structured problem presents the lenses for learners to view the problem in several ways and help learners engage in meaningful learning leading to the ability to think critically. Thus, the problem seems to stimulate learners critical thinking skills as indicated by the following excerpts

> *The problem scenario presented got me thinking of which aspect of science is connected to the problem and why because it was not like the regular question*

*presented to us in our normal classroom where I will refer to the textbook for a solution*

*(Aisha, interview, 23/03/2017).*

*Um... after searching in my textbooks and cannot find any link to defining the problem, I think concluded that the solution to the problem could not be found in the textbooks. Therefore, it got me thinking seriously*

*(Dami, interview, 23/03/2017)*

*The problem arouses my desire [inquisitiveness], and I was able to remember that, I watched a science programme about Genetically Modified Organism and concluded the problem was about genetic engineering*

*(Chetnum interview, 23/03/2017)*

The nature of the problem also helps the students to decide the course of action or to decide how to go about the problem, which requires the students to think about what to do. The students were able to identify the problem and the learning content that is needed to solve the problem

*I figure out two major aspects of the problem. First, I need knowledge about science, and mathematics that will be applied to solve the problem. Secondly, ideas on how to engineer [bioengineering] a unique rabbit*

*(Ezenwa, interview, 24/03/2017)*

The design-based learning worksheets seem to provide clues or guides for the students. The questions in the worksheets are divergent for example, at the beginning of the lesson students are presented with a scenario and are expected to fill the worksheet (KWHL) as highlighted in Figure 5.10

| What we know about the problem | what we need to find out | How do I proceed? | What we learned |
|---|---|---|---|
| | | | |

*Figure 5.10: KWHL work Sheet*

The students' verbal responses also buttress the fact that the questions and outline of the worksheet provided support as indicated in the verbal excerpts presented below;

> *Questions on the worksheet provided additional support through the different stages of the learning exercise*
>
> *(Chetnum Interview, 23/03/2017)*
>
> *the worksheet provided me with what to think and how to think, and the opportunity to write down my thoughts or ideas and reflect on them*
>
> *(Sheri Interview, 23/03/2017)*
>
> *The approach worksheet was structured according to the engineering phases which provided support for me to think from one phase to another*
>
> *(Ezenwa, Interview, 24/03/2017)*

The students were observed recording their ideas in their worksheets before meeting as a group to deliberate. The findings seem to suggest that the worksheets scaffolded the learners thinking as indicated in the excerpts of students' discussion in group 5 below

> *Zainab: What are we expected to do?*
>
> *Saraya: Hmm (.....) I think I followed the guidelines on the work skeet to answer the questions there for example, in the worksheets we are expected to write what we know about the problem first*

*Danju: The learning process is made up of five stages: First stage is defining the problem, second, generation of ideas (…..) I think let us start by defining the problem*

*(Verbal discussion, 10/03/2017)*

It was also observed that students used their worksheet to generate their ideas before meeting as a group to brainstorm at the end of each phase. The students' worksheets seem to mirror this major category as indicated in the excerpt below;

**Phase1: Engaging the Problem**

| Questions | Your Response |
|---|---|
| What are the facts about the problem | The client may be a marketer that sale rabbits who needs to improve his business |
| | The need to engineer a special rabbit that will be of economic benefit to the society |
| | The genetic modified rabbit should solve a problem in the society |
| Establish the goal of solving the problem | The unique rabbit will be a pet called Rabcat (combination of the features of rabbit and rat) with beautiful colours |
| Additional thoughts | The genetically modified rabbit will be sold by marketers to create employment and reduce unemployment in the society. |

Qualitative findings from this sub-theme suggested that learning clues such as the open-ended problem, learning phases and design-based worksheet seem to scaffold students' critical thinking skills. Therefore, the qualitative finding seems to corroborate the results of the quantitative data analysis presented earlier.

### c Question Prompts

Questioning and question prompt was an essential element that was embedded in iSTEMa. Although several techniques influence thinking skills among students' questioning, have the greatest impact (Duron et al., 2006; Preus, 2012). Hence, students' ability to think is directly proportional to the quality of questions and question prompt. It was observed that most of the questions the students and facilitator asked were divergent questions which may have enhanced the development of critical thinking skills.

The students' worksheets have questions prompts, for example, during the evaluation of the solution, the worksheets prompt the students for justification and evaluation as indicated in the figure below

**Phase 4: Evaluation of the Solution**

| Questions | Students' Responses |
| --- | --- |
| Was the goal requirement of solving the problem achieved? | If yes, why?<br><br>If no, why not? |
| Improve the design | Suggest how to improve the design |
| What are your major findings? | |

Prompting students for evaluation and justification of their solution or prototype could have scaffolded the development of critical thinking skills. The observation indicated students assessing their prototype based on the questions on the worksheet. The students advanced reasons why they think the goal of solving the problem is achieved on not. Because the students first reflect on what they have done and assess the prototype based on the purpose of solving the problem and advancing reasons for their decision. Thus, engaging in evaluation and inference sub-skills of critical thinking.

It was observed that the facilitator asked the students with questions prompts that seem to encourage critical thinking as highlighted in the excerpts of communication between the student and the facilitator. Group 7 was sitting quietly for some time, the teacher walks up to them and prompts them to think;

*Teacher; what have you done so far?*

*Shuna; We have agreed that our rabbit will be 10-15kg to serve as a source of protein.*

*Teacher; Why do you think this is a good idea*

*Sams; It is a good idea because in this part of the world rabbit meat is valued very well*

*Teacher; Any more proof?*

*Shuna; yes sir, that is why hunters hunt them to sell*

*Junior; That will also minimise the hunting of rabbits by farmers for meat, and we can preserve the extinction of the savanna hare.*

*Teacher; What other ideas emerge from the first phase*

*Kofiak; We thought of engineering a rabbit the can produce cod liver oil because of its medicinal value, but we settle for the other idea [unique rabbit to provide meat for our community].*

*Teacher; So why were you sitting quietly*

*Junior; The group leader asked us how we can achieve that which get us thinking about how that can be achieved*

*Teacher; okay continue but use your time very wisely.*

*(Verbal discussion, 3/03/2017)*

In view of the preceding, it suggested that the teacher engaged the students in evaluative thinking when he asked, "why do you think this is a good idea" The student response in the verbal interaction suggests the student was justifying their ideas.

Similarly, when the facilitator asked, "what have you done" this will stimulate the student to engage in reflection and explanation which may help them engage in interpretation. The student also asks a divergent question, for example, the group leader ask the students “how we can achieve that” this will engage the cognitive ability to propose solution or alternatives (inference sub-dimension). This finding corroborates the assertion that divergent or higher order thinking question help learners developed critical thinking skills (TEAL, 2013).

The entire learning process is driven by questioning. The questions are designed to encourage students' to think critically. Most of the question prompts by the facilitator, and the students offer the opportunity to engage in higher cognitive skills (analysis, synthesis, and evaluation) thus suggesting it could have assisted the students in acquiring critical thinking skills as indicated in the quantitative findings. Therefore, these findings corroborated the earlier findings of the quantitative data where there was a significant difference in students ability to thinking critically between iSTEMa and traditional group, in favour of the iSTEMa group.

### 5.12.2 Promote Cognitive Processes

In this theme, students' non-verbal behaviour and verbal behaviours during individual, and group interaction seem to suggest that the learners were involved in minds-on activities such as querying evidence for justification, examining ideas, assessing claims, analysing claims, proposing alternatives, identifying ideas. Students were also observed searching for relevant information from different sources, engaging in arguments, simulating inheritance of traits through the use of coins, and sketching their ideas. These non-verbal behaviours and verbal statements or accounts mirror the engagement of higher mental processes. Engaging in these higher mental or cognitive process could have led to the development of critical thinking skills among the participants. The processes highlighted above are group into five predetermines categories or sub-themes based on the critical thinking subskills adopted for this study; inference, recognising assumption, deduction, interpretation, and evaluation. Each sub-theme was define based on the nature of the mental process as highlighted in Table 5.29

Table 5.29

*Promote Cognitive Processes Subthemes and definition*

| **Category/Sub-theme** | **Definition** |
|---|---|
| Making Inference | Drawing an early conclusion based on available facts or information |
| Recognising Assumption | identify a statement that is assumed to be true and applicable or not without a proof |
| Deduction | Reasoning from the general to specifics |
| Interpretation | Students giving a brief explanation |
| Evaluation | Assessing ideas and making a conclusion based on facts |

a **Making Inference**

The findings indicated that the students provided some reasonable conclusion or explanation based on available information or facts on the phenomena. The findings suggest that the students or participants were engaged in making inferences, especially during group collaboration. For example, in the third ($3^{rd}$) task, the students in group 6 infer that it is the appearance of a new trait in a family. Group 2 were observed engaging in algebraic thinking of the likely genotype of the parents that could have resulted in the appearance of a new trait [albinism] in the family.

The students after considering several genotypes of the parents [algebraic thinking] draw an early conclusion that the parents must be heterozygous for the trait to manifest in the child. Verbal data suggesting that students were engaged in making inferences are presented below

> *My group was able to conclude on the appearance of a new trait in the family, that an individual can be normal but give birth to a child with an inherited abnormal condition like the case of the albino child because both parents were heterozygous for the trait*
>
> *(Sheri Interview, $23^{rd}$/03/2017)*

*I discover much information on the internet and based on this information I decided the information or ideas that were relevant to genetics [genetic principles such as heterozygous, homozygous] and ideas on problem scenario, such as bioengineering [genetic engineering] and decided that these are the two major ideas that are needed to solve the problem*

*(Chetnum Interview, 23rd/03/2017)*

based on the students understanding of the instructional content [principles of genetics were able to apply the knowledge to their personal life by concluding as indicated in the excerpts below

*…based on the principles of dominance and recessive, I was able to conclude that I am taller like my mummy not because I inherited the tallness from my mummy alone, but my mum's trait of height was dominant while my father's trait for height was recessive*

*(Hameed Interview, 23rd/03/2017)*

*…based on the principles of combination [genotypes]... the desired trait of our unique animal must be homozygous dominant to maintain the trait so that the farmer could continue to reproduce the animal*

*(Dami Interview, 23/03/2017)*

The students were observed engaging in making an early conclusion based on available facts (inference)

*The students were observed taking turns to present their ideas, after which all the members evaluate each idea, questions were asked for more explanations. Sometimes the students are seen engaging in an argument on the ideas presented but will eventually reach an amicable conclusion*

*(Observation, 2nd/03/2017*

The students were also observed making inferences while engaging in a group discussion or brainstorming at the end of each phase of the learning process. Almost all the groups engage in this cognitive processing for example, in group 4 as indicated in the following verbal discussion

*Dami: (Group leader) One of the ideas presented is for us to use selective breeding to get a unique offspring from the particular parent which the client will continue to breed*

*Ibro: I think the idea of using selective breeding for engineering a special animal is not relevant (…..) because if the offspring are heterogeneous and not homogeneous for the trait then not all the next offspring will be unique for the trait, (hmm..) we may have 3:1 ratio or 1:2:1. Secondly, there is nothing* *engineering in that idea because we are working on modifying the savannah hare to get a unique rabbit which is a genetically modified animal for our client,*

*Dami (Group leader) Any more observation or objection?*

*Students: no response*

*Dami (Group leader) I think we can conclude that the idea is not very good and applicable because there is nothing about science and engineering to be used to achieve the goal of the problem?*

*All other group members agreed*

*(verbal discussion, 2nd /3/2017)*

This findings on inference subskill of critical thinking appear to corroborate the quantitative result or findings where subskill of inference critical thinking skill of the students exposed to integrated STEM approach was enhanced.

b **Recognition of Assumption**

Ability to identify a statement that is assumed to be true without proof, it has to do with correctly appraising statements or arguments. It involves distinguishing weak arguments or information that is not an applicable and strong argument that applies to solve the problem (Watson & Glaser, 2008). This will involve asking questions for students to prove that the idea is weak or strong arguments. The ability of the students to identify ideas that are applicable and not applicable based on the information available and whether they are linked to the goal of the problem or not. Students' excerpts seem to illustrate recognising assumption.

*I assume that selective breeding could help us develop a unique organism that will be useful to society. This will involve selecting a male and a female animal with a desirable trait and allow them to mate. The offspring will manifest the unique features of the parents. The ideas were not applicable and the assumption was wrong*

*(Ezenwa, Interview, 24/03/2017).*

The lack of proof to show that the offspring from selective breeding will be unique and solve a problem in society clearly shows that learners demonstrate the ability to recognise an assumption that is not applicable.

The students were able to identify what they hold as an assumption compare to the knowledge they gained after participating in an iSTEMa learning of genetics. For example, the student holds an assumption that if you are tall like your mother, then you inherited the character tallness from her exclusively and independent of the father. After engaging in iSTEMa unit of instruction, the student discovers that traits are inherited from both parents. In this case, the gene for tallness from the mother was dominant and recessive. It will be important to stress that knowledge of dominant and recessive gene assist the students to engage in recognition of assumptions. The students' excerpts seem to buttress this.

> *"….I used to think I inherited the trait of tallness from my mother because she is tall while my father is short and similarly, I inherited my long nose from my father exclusively because my father has a long nose. I realise after the lesson that all traits are co-inherited from both parents but one allele of either the father or mother become dominant"*
>
> *(Bege, Interview, 24/03/2017)*

> *Compare the ideas with Mendelian principles and decide whether the idea align with my previous assumption*
>
> *(Dami Interview 23rd/03/2017).*

Group discussions seem to indicate learners are engaged in identifying information or ideas that were applicable or not given the goal of solving the problem as indicated in the excerpts from group six (6) below;

> *Bege (Group leader): Let us present our ideas on how to meet the requirement of the client*
>
> *Hill: my idea is to develop a breeding programme by selecting good looking and put them together in a cage or pence and allow them to give birth to young ones which may be unique and if not, we sell the offspring and repeat the process.'*
>
> *Bege: Is this relevant and applicable*

*Yarinya: Yes, it is relevant I think*

*Bege: why?*

*Fatima: maybe it is not relevant since the goal of the client is produce a unique rabbit, I think the offspring of selective breeding will not be related to the goal of the problem*

*(verbal discussion, 16th /02/2017*

The results seem to indicate students' engagement in cognitive processes leading to enhancement of recognising assumption. Consequently, the qualitative findings appear to support the conclusion of the quantitative result where the iSTEMa group gains more in the ability to recognised assumptions.

c **Deduction**

The findings from the data that mirror this category or sub-theme came from both verbal and non-verbal data. The data suggested that almost all the groups were involved in reasoning from general to specifics during minds-on activities and especially while defining the problem. The problem was presented as a general scenario, and from the scenario, students were able to come up with the specific ideas of solving the problem which suggests student engaging in deductive skills. An indication of deductive skills is observed as the students' reason from general to specific details as indicated in the excerpts as presented below.

*After highlighting what I know about the problem, I began in phase one by analysing the problem scenario into its parts using the worksheets this help me to see the details of the problem*

*Chetnum Interview, 23/03/2017)*

*From the problem scenario, I analysed the problem into two parts; The need for a special rabbit and secondly the rabbit should benefit humanity*

*(Aisha, Interview, 24/03/2017)*

*We break down the problem scenario that was presented into its meaningful parts to gain an understanding of the problem. The unique rabbit got me thinking on how the rabbit will look very special for our client*

*(Bege, Interview, 24/03/2017)*

The students seem to engage in deduction using a method they discovered during the generation of ideas. The non-verbal data below seem to indicate that;

> *The students were observed engaging in deduction using fork-lined [used to determine genetic and phenotypic ratio instead of punnet square] as a technology to engage in algebraic thinking and genetic probability*
>
> *(Observation, 2nd/03/2017)*
>
> *The teacher asked them how they came about using fork-line instead of punnet square, and Saraya one of the group's member replied I saw the idea on the internet, and I share it with my colleagues…. It easier and more interesting than punnet square*
>
> *(Observation, 2nd/02/2017)*

From the general problem scenario, students were able to come up with the specific goal of solving the problem, that is thinking from general to a specific purpose, thus engaging in deductive skills as indicated in the students' excerpts.

> *The goal of the problem is to deal with misconception or ignorance of heredity, that is in the problem scenario where there are crises in the family because of the appearance of a new trait [albinism]*
>
> *(Dami, Interview, 23rd/03/2017)*
>
> *Unravelling the appearance of a new trait in a family and the likely cause of the trait*
>
> *(Hameed Interview, 23rd/03/2017)*
>
> *Developing a unique, that will 10kg -15kg to serve as a source of protein and solve the problem of malnutrition in refugees' camp."*
>
> *(Aisha, Interview, 23rd/03/2017)*

These findings supported the quantitative data presented earlier that the approach influence students' acquisition of deduction subskill of critical thinking skills of the students in integrated STEM approach phenomenon. Suggesting that the approach helps the iSTEMa group developed the skill of deduction more than the traditional group d **Interpretation**

Generation of ideas about the problem and the knowledge of STEM disciplines, the students engage in the interpretation of the concept and principles of genetics that was applied to solve the problem. This refers to considering the evidence and taking a decision whether conclusions on the idea or evidence is necessary or warranted. The iSTEMa influence students' organisation of their thought process and help them clarify how they view ideas by judging ideas and providing an explanation.

The students were observed severally giving an explanation or making a clarification about their ideas; thus, this may suggest that students were interpreting. Saraya use a family tree to trace the appearance of a new trait in the family where a black and normal couples gave birth to an albino child to explain how the trait suddenly appeared

> *…the family tree of the family that discovered a new trait clearly showed that the albino trait was recessive in the grandparents and the parents (…..). However, dominant in the child that is why it is seen for the first time meaning the trait was inherited*
>
> *(Saraya Interview, 23/03/2017).*
>
> *In the first problem, the albinism became dominant in the child. Therefore, traits in offspring are inherited from both parents, but only the dominant character is observable.*
>
> *(Chetnum Interview, 23/03/2017)*

The students engage in interpreting their ideas especially during group discussion, the benefit of their unique animal. The students take turns to explain their ideas as indicated in the excerpts below;

> *I explain to group members that my unique GMO will solve the problem of unemployment through marketing our animal and reduce the problem of unemployment in the society because one of the requirement is that the unique animal will solve a problem in the society especially in Nigeria where unemployment is high*

*(Dami Interview, 23/03/2017)*

*We spend more time explaining how a unique animal will look like, and how the principles of science and mathematics will be applied to engineer the special animal. (umm) sometimes we disagree with others explanation and clarification but eventually agree and move on*

*(Hameed, Interview 24th/03/2017)*

Data from group discussion seems to indicate that students asked the group members for interpretation and explanation of their ideas. The findings suggest that the students were engaged in interpretation subskill of critical thinking skills as indicated in the excerpts presented below;

*Kofiak: oh yes, since we agree that our animal should be a pet, I decided to sketch the combination of the rabbit with a rat. Therefore, the size of the rat ear (pinna) was dominant in the pet. The name of the pet will be 'Rabrat.'*

*Shuna: Why "Rabrat"*

*Kofaik: The name means a pet engineered from the combination of the features Rabbit and Rat, the pet will also not be as big as rabbit and may not be as small as a rat*

*Dami: Wao… I think…. to make the pet more beautiful the ear (pinna) of the rabbit should be dominant because the ear is the distinguishing feature of the rabbit*

*(Observation, 9th /03/2017)*

These qualitative findings seem to complement the earlier quantitative data presented on interpretation critical thinking subskill. Indicating that the approach helps the iSTEMa group developed the skill interpretation

e **Evaluation of arguments**

The ability to differentiate among arguments that are strong and appropriate or relevant, as well as arguments that are weak and irrelevant to genetics and the problem. This was achieved by assessing the information to determine whether the idea was relevant or irrelevant. The Students' verbal data suggest that they engaged in evaluating arguments as indicated the excerpts below;

*I evaluate each idea presented based on the goal of the problem; to develop a unique genetic modified rabbit that will be useful to my society and how scientific principles can be applied to solve the problem. Example, a group member, suggested that the unique rabbit should be a source of protein to solve the problem of malnutrition and that was agreed. (Hameed Interview, 23/03/2017)*

The students highlighted that they engage in the evaluation of their ideas during group work

*In my group, every idea presented was assessed and a decision is reached whether it is good or not. All the good ideas are further assessed and agreed on the best idea for implementation*

*(Dami Interview, 23/03/2017)*

*Everyone presented at least an idea of making a total of six ideas, and then we study and evaluate the ideas one after the other to agree on one best idea that was accepted by all*

*(Saraya Interview, 23/03/2017)*

The students engage in building the prototype of their unique animal and thereafter assessed the prototype as indicated in the excerpts below

*…we assess our constructed unique rabbit, based on our assessment, our prototype looks good but could not stand very well, Ezenwa one of the students suggested we increase the thickness of the legs to make it strong.*

*(Aisha, Interview, 24/03/2017)*

Data from observation field notes suggest that during group discussion and generation of ideas, students may have engaged in evaluation assessing their opinions based on the requirement of solving the problem and the principles of science and mathematics.

*Aisha: umm…. my idea is to engineer a hare that can mimic camouflage any environment it finds itself because their numbers keep reducing because of the activities of predators and hunters.*

*John: What is the problem you are trying to solve and why*

*Yinum: The savanna hare is threatened by extinction by so doing we will solve the problem of its extinction because it will be difficult to be detected by hunters and predators. Secondly, this unique hare can be domesticated in a zoo because of its unique nature to provide attractiveness for fun seekers.*

John: *It sounds interesting but how will you go about it?*

*Hameed: we will get the slice gene from a Chameleon and engineer it into the skin of the Hare so that it can mimic the environment like the Chameleon*

*Dan: Any more explanation?*

*Hameed: The slice gene will be a dominant trait in the offspring based on the principles of dominance in Mendel's genetics*

*John (Group Leader): Can we consider this idea applicable based on the requirement*

*Riya: No but the idea looks interesting (hmm...) but let us take more ideas and then choose the best*

*(Observation, 16th /03/2017)*

In a related development and during hands-on activities students evaluated the prototype of their pet rabbit in activity 2 based on the question *is the goal of solving the problem achieved?*

*It was observed that, while others said yes and advance reasons for their pet rabbit by saying the rabbit is cute and attractive, Domba disagreed, pointing to the pet rabbit and remarked the legs are not very visible and suggested that " we need to find how to put legs or adjust it*

*(Observation 12th/03/2017)*

This finding on evaluating argument seems to triangulate the earlier findings of quantitative data on evaluating arguments dimension of critical thinking subskill. Indicating that, the iSTEMa created an environment that enhanced learners evaluate arguments or information.

## 5.13 Post-test Genetic Achievement Data Screening

Firstly, data screening was done to determine whether the assumption for parametric statistics (MANOVA). Furthermore, the validity of ANCOVA's result was based on the assumption of Normality, and the group variance must be equal or similar by yielding a p-value that is greater than 0.05($p > 0.05$). Data screening for normality, homogeneity of variance, and homogeneity of regression slope of the iSTEMa and traditional group post-test genetic achievement were as presented below;

### 5.13.1 Normality Investigation

Normal distribution of the post-test genetic achievement scores of iSTEMa and the traditional group was investigated to test the assumption of normality, and the result presented numerically and graphically for each group. Kolmogorov-Smirnov test and Shapiro-Wilk test was the numerical method employed to check for normality. The result is as presented in Table 5.30.

Table 5.30

*Kolmogorov-Smirnov Test and Shapiro-Wilk Test for iSTEMa and Traditional Group Genetic Achievement Post-test Scores*

| Variable | Groups | Kolmogorov-Smirnov[a] | | | Shapiro-Wilk | | |
|---|---|---|---|---|---|---|---|
| | | Statistic | df | *P*-value | Statistic | Df | *P*-value |
| Genetic Score | iSTEMa | .10 | 51 | .20* | .97 | 51 | .44 |
| | Traditional | .10 | 49 | .20* | .97 | 49 | .40 |

Table 5.30 indicates normality test for iSTEMa and traditional group in genetic achievement. The Kolmogorov-Smirnov test and Shapiro-Wilk test for the iSTEMa group p-value were .200 and .447 respectively which is greater than 0.05 ($p>.05$). While the traditional group has a p-value of .200 and .409 which is also higher than 0.05 for Kolmogorov-Smirnov test and Shapiro-Wilk test respectively, therefore, the data is said to be approximately normal, since the assumption of normality was not violated, the data was analysed using inferential statistics.

The result is further presented in the form of a histogram to highlight normal distribution visually. The histogram of iSTEMa and the traditional group was presented in Figure 5.10 and 5.11

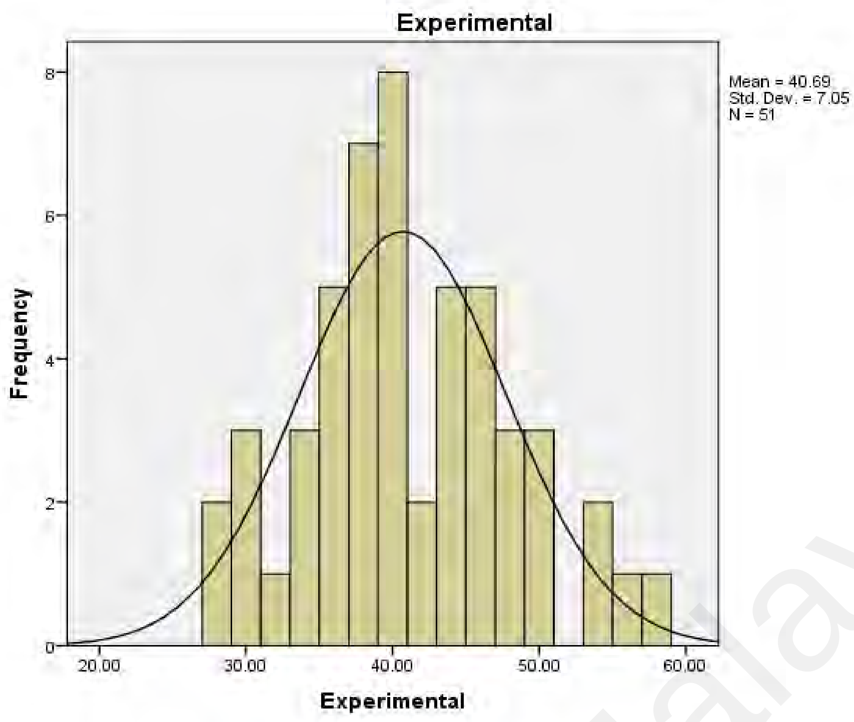


*Figure 5.11.* Histogram for iSTEMa group Genetic achievement Score

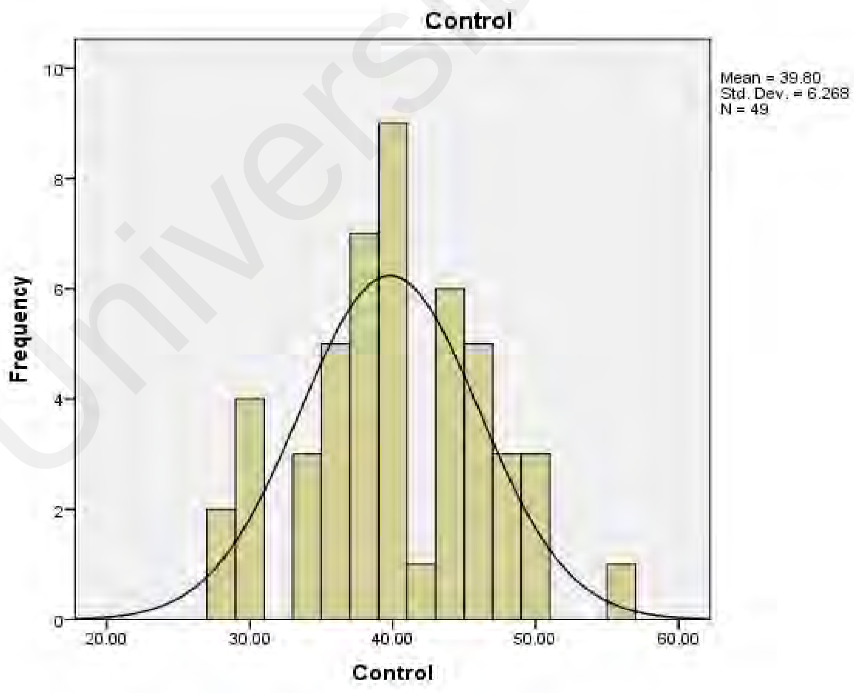


*Figure 5.12.* Histogram for Control Group Genetic Achievement Score

Figure 5.10 and 5.11 shows the visual histogram output of the iSTEMa and traditional group respectively, the histograms of the two groups seem to have a fairly accurate shape of a normal curve. Therefore, it can be assumed that the genetic achievement data of the two groups are approximately normally distributed.

### 5.13.2 Homogeneity of Variance

Homogeneity of variance assumption was scrutinise using Levene's test, the analysis of homogeneity of variance of genetic achievement data is presented below;

Table 5.31

*Test of Homogeneity of Variances for Post-test Genetic Achievement between Experimental and Control*

| Genetic Achievement | Levene Statistic | df1 | df2 | *P-value* |
|---|---|---|---|---|
| Terminology | .10 | 1 | 98 | .74 |
| Mendel's Laws | .11 | 1 | 98 | .74 |
| Probability | .03 | 1 | 98 | .86 |
| Overall Score | .69 | 1 | 98 | .40 |

Table 5.31 clearly shows that the subscale genetic terminology result was $F(1,98) = .104$, $p(.747) > .05$, Mendelian laws $F(1,98) = .111$, p(.740) >.05, genetic probability $F(1,98) = .031$, $p(.861) > .05$, which did not violates the assumption of homogeneity of variance. Subsequently, the overall Levene's result of the iSTEMa and traditional groups was $F(1,98) = .695$, $p (.406) > .05$, did not violate the assumption of homogeneity of variance. It is, therefore, concluded that the iSTEMa and traditional group variance were identical for genetic achievement post-test results. Consequently, inferential statistics (MANOVA) was employed to test the formulated hypotheses.

### 5.13.3 Homogeneity of Regression Slope for Genetic Achievement

The independent variables are the iSTEMa and traditional group. The dependent variable is the overall genetic score. While the covariate is the pre-test score. The results for homogeneity of regression slope for genetic achievement score for the two groups are as presented in Table 5.32

Table 5.32

*Homogeneity of Regression Slope for Genetic Achievement of iSTEMa and Traditional Group*

| Source | Dependent Variable | df | Mean Square | F | *P*-value |
|---|---|---|---|---|---|
| Intercept | Terminology | 1 | 3221.49 | 437.32 | .01 |
| | Mendel's laws | 1 | 2876.28 | 406.72 | .01 |
| | Probability | 1 | 2880.55 | 561.82 | .01 |
| | Overall | 1 | 27252.3 | 652.89 | .01 |
| Group * | Terminology | 2 | 5.33 | .72 | .48 |
| Terminology * | Mendel's laws | 2 | 14.89 | 2.10 | .12 |
| Mendel's Laws * | Probability | 2 | 12.31 | 2.40 | .09 |
| Probability * Overall post-test | Overall | 2 | 86.67 | 2.07 | .13 |
| Error | Terminology | 96 | 7.36 | | |
| | Mendel's laws | 96 | 7.07 | | |
| | Probability | 96 | 5.12 | | |
| | Overall | 96 | 41.74 | | |

Table 5.32 shows the homogeneity of regression slope for iSTEMa and traditional group on genetic achievement. The results were not significant in all the subsection of genetics ($p > .05$). The overall results of post-test genetic achievement for the two groups were $F$ (2, 96) = 2.077, $p$ (.13) >.05. We fail to reject the hypothesis of the assumption which states there is no significant homogeneity of regression slope between iSTEMa and traditional group. Indicating the assumption of homogeneity of regression slope of variance was not violated.

## 5.14 Descriptive Statistics of Pre-test and Post-test genetic Achievement of iSTEMa and Traditional Group

To answer the research question which states is there any significant mean difference in genetic achievement between senior secondary school students that learn with iSTEMa and those who learn using the traditional method? Descriptive statistics were employed to determine the differences between integrated STEM approach and the traditional teaching method in enhancing students' achievement in genetics. Mean, and the standard deviation was calculated for both pre-test and post-test for both iSTEMa and traditional group in the three subscales of genetic achievement (terminology, Mendel's laws, and probability). The result is presented in Table 5.33

Table 5.33

*Means and Standard Deviation Comparison of pre-test and post-test Genetic Achievement of iSTEMa and Traditional Group*

| Genetic Achievement | Group | Pre-test | | Post-test | | Mean Gain |
|---|---|---|---|---|---|---|
| | | Mean | SD | Mean | SD | |
| Terminology | iSTEMa N (51) | 9.62 | 2.82 | 11.92 | 2.75 | 3.30 |
| | Traditional N (49) | 12.04 | 2.58 | 13.28 | 2.90 | 1.24 |
| Mendel's Laws | iSTEMa N (51) | 10.33 | 2.82 | 15.20 | 4.51 | 4.87 |
| | Traditional N (49) | 10.81 | 2.54 | 13.61 | 4.00 | 2.80 |
| Genetic Probability | iSTEMa N (51) | 10.29 | 2.33 | 13.56 | 3.21 | 3.27 |
| | Traditional N (49) | 10.51 | 2.25 | 12.89 | 3.09 | 2.83 |
| Overall | iSTEMa N (51) | 30.45 | 6.39 | 40.68 | 7.04 | 10.23 |
| | Traditional N (49) | 33.59 | 6.66 | 39.79 | 6.26 | 6.20 |

Table 5.33 shows the descriptive statistics of the iSTEMa and traditional group. The pre-test means and standard deviation of the iSTEMa group in terminology are 9.62 and 2.82 respectively, while the post-test means, and standard deviation were 11.92 and 2.75 respectively. On the other hand, the traditional group pre-test and post-test mean were 12.04 and 13.28 respectively. The standard deviation for pre-test and post-test were 2.58 and 2.90 respectively.

In Mendelian laws subsection the pre-test and post-test mean were 10.33 and 15.20 respectively, standard deviations were 2.82 and 4.51 respectively. On the other hand, traditional group pre-test and post-test means were 10.81 and 13.61 respectively, while the standard deviations were 2.54 and 4.00 respectively. Genetic probability pre-test and post-test means were 10.29 and 13.56 respectively, standard deviation 2.33 and 3.21 respectively. While traditional group pre-test and post-test means were 10.51 and 12.90 respectively, while the standard deviations were 2.52 and 3.09 respectively. The overall pre-test and post-test mean 30.45 and 40.68 respectively, the standard deviation of the two times were 6.39 and 7.04 respectively. The traditional group pre-test means, and post-test mean 33.59 and 39.79 respectively, while the standard deviations were 6.66 and 6.26 respectively.

Given the preceding, the means were compared to determine the mean difference between iSTEMa and traditional group in the post-test. The post-test means the gain of the iSTEMa group in three subsections of genetic achievement; terminology, Mendelian Laws and genetic probability were 3.30, 4.89, and 3.27 while the overall mean gain for the iSTEMa group is 10.23. While the traditional group main in terminology, Mendelian Laws and genetic probability were 1.24, 2.80 and 3.09 respectively. The overall mean gain for the traditional group is 6.20. The mean difference between the iSTEMa and traditional group in a subsection of genetic achievement; terminology, Mendelian Laws and genetic probability were 1.06, 2.07 and 0.44 respectively. The overall mean difference in the post-test for the iSTEMa and traditional group is 4.03. The result is highlighted as in Figure 5.13

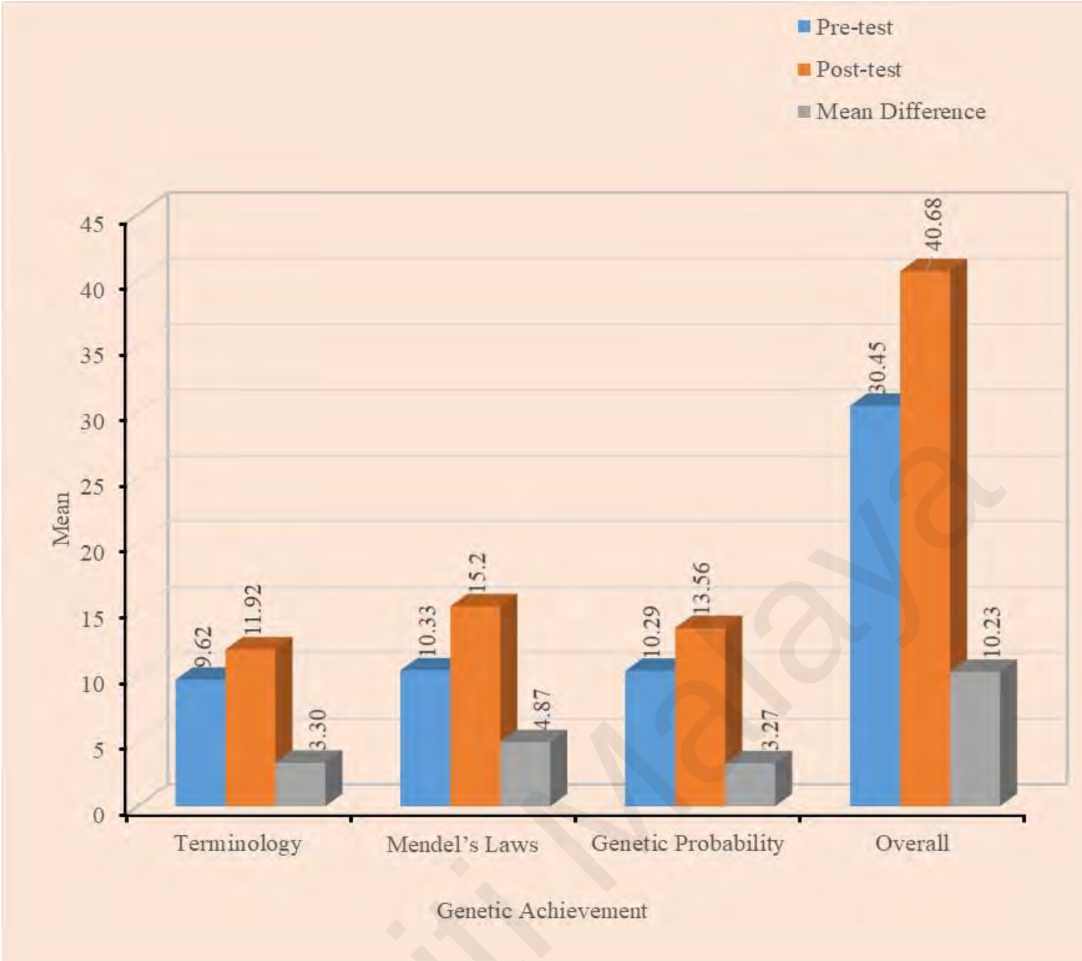


*Figure 5.13 Between Groups Mean Gain Comparison*



Figure 5.13 indicates that the iSTEMa group performed better than the traditional group in all three subsections of genetic achievement (Terminology, Mendel's Laws and Genetic Probability. This implies that the iSTEMa was more effective than traditional teaching methods. MANOVA was used to determine whether the mean difference between the groups was significant or not.

## 5.15 Post-test Genetic Achievement

This is to test hypothesis two which states that there is no significant difference in the achievement of senior secondary school students' in genetic concepts between senior secondary school students that learn with iSTEMa and those who learn using the traditional method. Both within-group comparison and between-group comparison were employed to determine students' post-test achievement in genetics.

### 5.15.1 Within-Group Comparison of Genetic Achievement

The mean comparison of within-group was performed that is, between the pre-test and post-test to determine whether the effects of treatment were significant or not. The dependent t-test was employed for the analysis, and the result is presented below.

Table 5.34

*Within-Subject Comparison of Genetic Achievement*

| **Dimension** | **Group** | **Pre-test mean ± SD** | **Post-test mean ± SD** | ***df*** | ***t-value*** | ***p-value*** | ***d²*** | |
|---|---|---|---|---|---|---|---|---|
| Terminology | iSTEMa | 9.62±2.82 | 11.92±2.75 | 50 | -5.71 | .01 | 0.82 | Medium |
| | Traditional | 12.04±2.58 | 13.28±2.90 | 48 | -2.55 | .01 | 0.45 | small |
| Mendel's Laws | iSTEMa | 10.33±2.82 | 15.20±4.51 | 50 | -7.43 | .01 | 1.29 | large |
| | Traditional | 10.81±2.54 | 13.61±4.00 | 48 | -4.38 | .01 | 0.83 | large |
| Probability | iSTEMa | 10.29±2.33 | 13.56±3.21 | 50 | -6.24 | .01 | 0.94 | large |
| | Traditional | 10.51±2.52 | 12.90±3.09 | 48 | -4.10 | .01 | 0.84 | large |
| Overall | iSTEMa | 30.45±6.39 | 40.68±7.04 | 50 | -9.03 | .01 | 1.52 | large |
| | Traditional | 33.59±6.66 | 39.79±6.26 | 48 | -5.18 | .01 | 0.95 | Large |

The result in Table5.34 shows that there were statistically significant differences between the pre-test and post-test of iSTEMa and traditional group in genetic achievement. The *p-value* in all the genetic achievement sub-categories of terminology, Mendel's laws and the probability of both the iSTEMa and traditional group were less than .05 ($p$<.05), indicating significant difference in both the experimental and control group. The effect size of Terminology, Mendel's law and probability were medium, large and large respectively. Similarly, the control group has the effect size of small, large and large for terminology, Mendel's laws and the probability respectively. The overall genetic score for the iSTEMa group indicated a significant difference $t(50) = -9.03$, $p(.01) < .05$; $d^2=1.52$, this suggests that the mean difference between the pre-test and post-test of students' that learn with iSTEMa was significant, the effect size was large. Similarly, the traditional group overall result showed a significant difference $t(48) = -5.18$, $p(.01) < .05$; $d^2=0.95$ This implies that the mean difference between the pre-test and post-test of students taught with the traditional teaching method was significant, the effect size was large (Cohen, 1988). Therefore, the two groups gained significantly from treatment.

### 5.15.2 Between-Subjects Comparison in Genetic Achievement

The mean of the iSTEMa and traditional group in the genetic post-test was compared to determine the effects of iSTEMa. Multivariate analysis of Covariance (MANCOVA) was used. The MANCOVA was used as a single test for the subsection of genetic achievement (terminology, Mendel's laws, genetic probability, and the overall results) instead of performing multiple individual tests of each subsection. MANCOVA was used because there was a significant difference in the pre-test score between the two groups before treatment. Therefore pre-test is used as a covariate (Howell, 2007). Since there was no violation of any of the assumptions, Wilks' Lambda was used to interpret the results. The findings are as presented in Table 5.35

Table 5.35

*MANOVA Results for Post-test Genetic Achievement Test*

| Effect | | Value | F | df | Error df | *P-value* | Partial $\eta^2$ |
|---|---|---|---|---|---|---|---|
| Intercept | Pillai's Trace | .53 | 36.57 | 3 | 95 | .00 | .53 |
| | Wilks' Lambda | .46 | 36.57 | 3 | 95 | .00 | .53 |
| | Hotelling's Trace | 1.15 | 36.57 | 3 | 95 | .00 | .53 |
| | Roy's Largest Root | 1.15 | 36.57 | 3 | 95 | .00 | .53 |
| Pre-test | Pillai's Trace | .15 | 5.63 | 3 | 95 | .00 | .15 |
| | Wilks' Lambda | .84 | 5.63 | 3 | 95 | .00 | .15 |
| | Hotelling's Trace | .17 | 5.63 | 3 | 95 | .00 | .15 |
| | Roy's Largest Root | .17 | 5.63 | 3 | 95 | .00 | .15 |
| Group | Pillai's Trace | .08 | 2.85 | 3 | 95 | .04 | .08 |
| | Wilks' Lambda | .91 | 2.85 | 3 | 95 | .04 | .08 |
| | Hotelling's Trace | .090 | 2.85 | 3 | 95 | .04 | .08 |
| | Roy's Largest Root | .090 | 2.85 | 3 | 95 | .04 | .08 |

Table 5.35 shows that there is a significant difference between the iSTEMa and the traditional group in the subscales and overall genetic achievement. Wilks' Lambda $\wedge = .91$, $F(3, 95) = 2.85$, $p = (0.04) < 0.05$. Therefore, the between-subject effects were presented to determine the source of a significant difference. The result is as presented in Table 5.36.

Table 5.36

*Test of Between-subject effects on Post-test Genetic Achievement*

| Source | Dependent Variable | Df | Mean Square | F | *P*-value | Partial Eta Squared |
|---|---|---|---|---|---|---|
| Pre-test | Terminology | 1 | 112.08 | 16.18 | .00 | .143 |
| | Mendel's Laws | 1 | 27.28 | 1.50 | .22 | .015 |
| | Probability | 1 | 1.07 | .10 | .74 | .001 |
| | Overall Score | 1 | 218.22 | 5.09 | .02 | .050 |
| Group | Terminology | 1 | 17.04 | 2.46 | .12 | .025 |
| | Mendel's Laws | 1 | 79.68 | 4.38 | .03 | .043 |
| | Probability | 1 | 9.07 | .90 | .34 | .009 |
| | Overall Score | 1 | 61.01 | 1.42 | .23 | .014 |
| Error | Terminology | 97 | 6.92 | | | |
| | Mendel's Laws | 97 | 18.19 | | | |
| | Probability | 97 | 10.04 | | | |
| | Overall Score | 97 | 42.81 | | | |

Table 5.36 shows the between-subject comparison of the genetic subsection of the two groups. The result indicates there was no significant difference between the iSTEMa and traditional groups in genetic terminology dimension $F(1, 97) = 5.815$, $p = (0.12) > 0.05$, with the mean of the traditional group (13.28) was not significantly higher than the mean of the iSTEMa group (11.92). The partial $\eta^2 = .025$, indicating that approximately only 2.5% of the total variance of genetic terminology is accounted for by the instructional approaches.

There is no significant difference between the iSTEMa and traditional group in Mendelian laws subsection $F$ (1, 97) = 4.381, $p = (0.039) < 0.05$. The partial $\eta^2 = 0.034$, indicates that, approximately only 3.4% of the total Mendelian Laws score is accounted for by the instructional approach. The iSTEMa group means (15.19) which is higher than the mean of the traditional mean (13. 61).

There was no significant difference between the iSTEMa and traditional group in probability $F(1, 97) = .904$, $p = (.344) > 0.05$. The partial $\eta^2 = 0.009$, indicating that approximately only 0.9% of the total genetic probability score is accounted for by the instructional approach. The iSTEMa group means (13.53) which is higher than the mean of the control (12. 89).

In the overall result of students' achievement in genetics there was no significant difference between the iSTEMa and traditional group in genetic achievement $F(1, 97) = 1.425$, p = (0.235) > 0.05, The partial $\eta^2$ =0.014 indicating that approximately only 1.4% of the overall genetic score is accounted for by the instructional approach. The mean of the iSTEMa group ($M$ = 40.68) which is higher than the mean of the traditional group ($M$ = 39.79). This indicates that the mean difference (1.58) between the iSTEMa and traditional group in genetic achievement was not significant. Therefore, the hypothesis which states that there is no significant difference in the achievement of senior secondary school students' in genetic concepts between senior secondary school students that learn with iSTEMa and those who learn using the traditional method was rejected.

## 5.16 How iSTEMa Improved Students' Achievement in Genetics

The qualitative findings from interview and observation field notes suggested that students learning with iSTEMa appear to be characterised by an individualised and collaborative engagement which could have enhanced meaningful learning through the presentation of ideas, peer learning, sketching and building of artefacts which may have improved students' academic achievement. This seems to agree with Mehta and Fine (2019) who reported that deeper learning is associated with individualised learning, social interaction and cognitive engagement. These experiences as described by the students are categorised into two themes. Interaction, and engaging activities, which were elaborated in the next subsections below

### 5.16.1 Learning Interaction

Students interview responses and observation field notes provide evidence that could be described as interaction. It was observed that students rearranged their seats in a semi-circular form to face each other with their worksheets and writing materials in front of them. This suggests that this physical arrangement was to facilitate interaction and exchange of ideas among members of the group. This theme was made up of sub-theme such as students' interaction, Peer tutoring, and student and teacher interaction. These sub-themes are highlighted in a tabular form as presented in

Table5.37 (indicating the theme, subcategory and their definition) and was discussed in the next section.

Table 5.37

*Sub-theme and their definition*

| **Theme** | **Category/Sub-theme** | **Definition** |
|---|---|---|
| Learning Interaction | Students interaction | Exchange of ideas among learners with the view to achieving the learning objectives |
| | Peer Tutoring | Tutoring and co-learning among students in a group where students help each other learn |
| | Teachers/students interaction | Learning interaction between the students and the facilitator to enhance the students learning and cognitive engagement |

a **Students Interaction**

Interactions or collaboration among learners characterises the integrated STEM approach. Activities such as exchange of ideas among learners, probing each other, communicating, arguing and defending opinions are classified under this sub-theme (students' interaction). The sitting arrangements in the treatment class seem to buttress this subtheme as observed

> *The students' seating arrangement was observed to be adjusted in a semi-circular way, such that the students sit facing each other in the iSTEMa group. On the contrary, the traditional group sits facing the teacher in front of the classroom. Thus, the seating arrangement seems to encourage interaction among group members*
>
> *(Observation, 9th /02/2017).*

The students work individually to search for relevant information and ideas and meet in a group to brainstorm and interact. This was demonstrated in the verbal excerpts presented below.

*Group discussion assist me in getting different views or opinion on genetics and genetic engineering. Group members response to any idea help you to gain more insight and understanding*

*(Aisha Interview 24th/03/2017)*

*"….unlike in our regular classes where we keep quiet and listen to the teacher, this time the class was quite noisy, each group was busy discussing and sometimes arguing with one another, and everyone participated by sharing their ideas*

*(Fatu Interview 24th/03/2017)*

Students seem to move from generating ideas individually to group interaction during the learning process. The students acknowledge the importance of teamwork or learning in a social context as indicated in the following students' excerpts;

*I have gained the skills of working in a group, listen to other people ideas and ask a question (such as what your opinion is?) that will make other members express their ideas*

*(Kofiak Interview, 24th/03/17).*

*I discovered that the best way to solve the problem is through teamwork and collaboration because from three or four ideas in my group we were able to come up with a better idea*

*(Sheri. Interview, 23rd/03/2017)*

*I gained a new perspective during group interaction. My mind was always alert thinking of how to defend my idea or what meaningful contribution to make to the discussion. It makes me think well [more]*

*(Dami, Interview 24th / 03 /17)*

During group interaction, students were observed presenting their ideas and justifying their position as other members of the group seek for clarity. Students were seen engaging in the reflection of what has been done in the previous phase.

*John (group leader): Before considering our ideas, in summary, let us remind ourselves of the components or requirement of the problem*

*Hameed: The elements of the problem are; engineer a unique rabbit;*

*John: The unique Rabbit should solve a given problem in society;*

*Group leader: Any more*

*Riya: yes, it should be beneficial to the community, and the savannah hare is peculiar to Africa*

*John; can we take the first idea*

*Finum; Engineer a rabbit that can glow in the night, I think that will be unique and very special, and the client may love it.*

*Kajuro: interesting (….) but how can that be achieved*

*Finum; The gene of the Jellyfish will be extracted and isolated and inserted into the DNA of the rabbit. The genetically modified rabbit will glow in the night.*

*Hameed; Yes meaning we will have a savannah rabbit the will glow in the night [ ] that will be interesting*

*(Observation, 3rd /03/2017).*

The students seem to engage in co-construction of ideas during group interaction and discussion as indicated in the observation field notes. Students were also observed presenting several ideas, all the ideas were reviewed, and the best idea was adopted, or sometimes a new idea is developed from the ones presented.

*During group collaboration, we try to figure out what will work best and what will not by identifying good ideas. We deliberated on the good ideas to reach a consensus on the best idea*

*(Sheri, Interview 23rd/03.2017).*

*…we developed many ideas, that will not be possible by one person alone, I gained a lot from my group members*

*(Bege, Interview 24th /03/2017).*

During teamwork, students' mental or cognitive structure may have been modified based on the following students' excerpts

*I used to think it God that created everyone appearance and traits but realised that I inherited almost every character from my parents through heredity*

*(Fatu, Interview 24th/03/2017)*

*I thought engineering is a course that is relevant at the university level but comes to realise that there is an interplay between science and engineering in problem-solving.*

*(Kofiak, Interview, 23/03/2017)*

Individual student participation in group work must have inspired the appraisal of their ideas which helps them to decide.

*For me, my unique rabbit should be the one that can run faster than all the predators and have a similar colour to the environment, with that we can prevent it from being kill by wild animals and preserve it but we agree this will not meet the goal of the problem =*

*= A group member idea was to engineer a rabbit that can be used as a pet with beautiful colours which we will sell and make money. The group member also deliberated on which colour will be attractive; one said pink because women like pink and another said white because white is beautiful while another suggested blue because it stands for love*

*(Saraya, Interview, 23rd /03/2017).*

*"We finally agreed in our group [group 6] that our pet animal should be smaller than the Savannah Hare and the colour should be yellow, and white."*

*(Bege, Interview, 24th /03/2017)*

Students' interactions among themselves promote active learning leading to a deeper understanding of science concepts and enhance critical thinking skills acquisition. This agrees with Kim et al. (2013) who reported earlier that collaborative instruction enhances critical thinking development. Therefore, These qualitative findings support the quantitative results presented earlier where the group exposed to iSTEMa performed better in genetic academic achievement

b **Peer Tutoring**

The students were observed helping each other to learn in the entire process by providing explanation and clarification, especially about genetic concepts, principles, and terminologies. These interactions were categorised as peer tutoring. In other words, this sub-theme focused on students assisting each other to learn and acquire the related knowledge and skills. This is demonstrated in the following interview excerpts

*I did the work with my group members most of the time and some of the things I do not understand [punnet square] my group members demonstrated it to me using a monohybrid cross*

*(Chetnum Interview, 23/03/2017)*

*Mendel's second law of independent assortment was difficult to understand, but during group interaction, the group leader takes time to explain, and it became clearer to me*

*(Aisha, Interview 24th / 03 /17)*

The students tutor each other on genetics and probability. This seems to change their misconception on some genetics processes or concepts as demonstrated in the following excerpts.

> *"I had misconception how traits are inherited, I thought a child inherit one trait from the father and another from the mother, but now I understand from the group leader's explanation that the child inherits half of the trait from each parent."*
>
> *(Sheri, Interview 23rd /03/2017).*
>
> *Genetic terminology {dominant, recessive, homozygous, heterozygous….] was confusing to understand, but other members of my group explained it better, and it became clearer to me. Dami told me that dominant is the opposite of recessive while the meaning of homozygous is q dominant trait example TT for tallness while heterozygous is Tt for tallness*
>
> *(Fatu Interview 24th/03/2017)*

The observation field notes data suggested that students were tutoring each other many times the students shift roles between tutor and tutee. Students engage in chunking of informational to explain some genetic concepts.

> *Luka explains to his group members that the best way to understand genetic terminology is by viewing them in positive and negative. He said dominant /recessive, genotype/ phenotype, Homozygous/heterozygous =*
>
> *= He explained that dominant is like the opposite of recessive and explained the genetic terminologies and some of this principle to each other.*
>
> *Dami one of the students ask, please show me how to determine phenotypic and genotypic ratios from the data we collected*
>
> *Kofiak: replied it is very simple, bring the data you have generated... The phenotype is the physical appearance of the offspring, He pointed to the data and explained how probability could be determined as well as phenotypic and genotypic ratios*
>
> *Dami; thank you.*
>
> *(Observation, 7th/03/2017)*

The students assisted each other on how to perform some task on the computer. The following interaction indicates peer tutoring among students as observed by the researcher.

> *Kura: please, I forgot how to open this document on a new page (pointed to the document on the screen)*
>
> *Fatu: you mean a new tap*
>
> *Kura: yes .. I think so*
>
> *Fatu: To open in a new tap (look) put the cursor on the item, right click and select open in new tap (there you go)*
>
> *Kura; Wao …. Simple*
>
> *(Observation, 15th /03/2017)*

The learning environment was more collaborative than individualised. The participants seem to interact within their groups and between members of one group and another as indicated in the excerpts

> *It was observed throughout the learning process students interact within members of their group and members of another group.*
>
> *Example Numa in group seven (7) ran to group two (2) and asked Praise "how do we define the problem? Hmm.. study your student worksheet Praise replied.*
>
> *It was observed that the classroom was slightly noisy, each group engaging in teamwork, exchange of ideas and tutoring. This seems to indicate that students actively participated in the learning process*
>
> *(Observation, 15th /03/2017)*
>
> *We work individually to generate ideas and collectively to decide the best idea and participate in the group project. I learn better this way especially from group members rather than just listening to the teacher or check the textbooks*
>
> *(Hameed, Interview, 23rd /3/2017)*

It can, therefore, be inferred that peer tutoring scaffolded the students individually and as a group to be active and engage in minds-on activities through question prompts. This may have enhanced students learning of genetics and critical thinking skills. Therefore, the findings of the qualitative data on peer tutoring seem to support the earlier results of the quantitative data presented earlier c **Teachers/Students Interaction**

The teacher seems to guide the students with divergent questions (why, how and what), encourage higher cognitive engagement, exploration of the learning content, and classroom management. On the other hand, students ask for help from the teacher when they are stuck. All these are classified under the sub-theme teacher-student interaction.

It was observed that the facilitator was moving from one group to another observing what they were doing and interacting with the students, asking questions that will guide them. This is indicated in the excerpts of interaction between group 9 students and the facilitator;

*Jom: please sir we do not know what to do and where to start?*

*Teacher: What are you expected to do*

*Ezenwa: Hmm(…..) I think to follow the guidelines of the work skeet to carry out the task, for example, in the first part of the worksheets we are expected to write what we know about the problem*

*Mercy: The learning process is made up of five stages: we are supposed to define the problem.*

*Teacher: good, but before you define the problem, what do you know about the problem?*

*Jom: hmm… It is about animal breeding, and we were taught something similar to this in agricultural science.*

*Baba: yes (…..) it is about heredity and probably genetic engineering*

*Teacher: Anything more about the problem?*

*Students: (pause)*

*Teacher: begin by writing what you know about the problem=*

*=I will be back to see how far you have gone (walk away to another group)*

*(Observation, 23/02/2017)*

The above questions by the teacher (what do you know about the problem?) serve as a cognitive scaffold which engages the learners' higher order thinking skills which is very vital to the development of critical thinking skills and deepens the understanding of the instructional content. The question will also activate and engage student prior knowledge which is also vital for meaningful learning to take place. The approach was learner centred; however, the student acknowledged the role of the teacher-student interaction which has scaffolded their learning as indicated in the excerpts below.

> *With the support of the teacher, we took different roles [father and mother, two coins representing the alleles of the two] to demonstrate how traits are inherited and determined the ratios, probability, and percentages of the offspring that help me understand genetic probability.*
>
> *(Aisha, Interview 23rd/03/2017)*

It was also observed that the facilitator helps learners engage in meaningful collaboration and individuals in the group that seems to be quiet are involved in the group discussion as indicated below;

> *Teacher: Baba what do you think of what the group leader said? Asked the facilitator*
>
> *Baba: hmm nothing.*
>
> *Teacher: tell us what you and the group have done so far?*
>
> *Baba: yes, we started in phase one by defining the problem (please have a look at my worksheet).*
>
> *Teacher: I will look at that later but explain to me.*
>
> *Baba: after defining the problem individually, we then met at the group to interact and agree on the goal of solving the problem (my unique rabbit is a rabbit that can mimic the environment). In the last lesson, we spend time searching for ideas on the internet and textbooks on how that can be achieved.*
>
> *Teacher: what next? We are back in our group to share our ideas and agree on the best idea*
>
> *(Observation 12/03/2017).*

It can, therefore, be inferred that teacher-student interaction helps the students to stay on track and within the learning objectives, it also scaffolded the students to engage in minds-on activities through question prompts. This may have influenced the achievement of the iSTEMa group better than the traditional group. Therefore, the findings of the qualitative data supported the earlier findings of the quantitative data presented earlier.

### 5.16.2 Engaging Activities

Learners engaged in several activities during learning process using integrated STEM approach. Activities such as searching for ideas from the internet and textbooks about genetic laws, rules of combination and the rules of expression (genotype and phenotypes). The activities seem to be engaging because there are three components of content knowledge students need; knowledge about the content of science and mathematics to be integrated, knowledge on genetic engineering and idea how to develop or build the solution.

The students were observed sketching their ideas on how their unique animal should look like as indicated below

*Figure 5.14. Students' sketching*

The students were observed building their hare, engaging in group project based on the goal of solving the problem

*Figure 5.15. Students' Group project*

Finding from the data seems to mirror the sub-theme challenging activities. The student explores the internet and textbooks for relevant ideas. Indicating that the students were responsible for their learning as indicated in the students' excerpts presented below;

> *To find a solution to the goal of the problem scenario, we searched for information [searching for information] about genetics principles, and laws as well as how genes combine to form a trait and how these traits expressed itself in the offspring from the textbooks and the internet*
>
> *(Kofiak Interview, 23rd/03/2017)*

> *First, each member of my group searches for some genetic principles, and concepts for understanding from our biology textbook and the internet. I search form both the internet and textbooks, read to see whether what I search was relevant or not*
>
> *(Chetnum Interview, 23rd/03/2017)*

> *Using local materials to translate our ideas into an imaginary animal was one of the activities that make us work like engineers, we tried severally using different materials before we settle with using cardboard paper and cartons, gums and markers*
>
> *(Sheri, Interview, 23rd/03/2017)*

> *Sketching my ideas and meeting in a group to exchange ideas are some of the ideas that were interesting to me*
>
> *(Fatu Interview, 24th /03/2017)*

Non-verbal data from observation field notes suggested that learners engage in hands-on activities with their group members to demonstrate how traits are inherited by offspring. Students were also observed experimenting with extracting the DNA from living tissue

> *The students were observed searching and reading their books while others were seen searching for relevant information and ideas from the internet. Some students were observed jotting down information from the internet and textbooks. Students are always excited to meet in a group to brainstorm and share ideas. Students are heard arguing and defending their ideas among group members*
>
> *(Observation, $2^{nd}$ /03/2017)*
>
> *Students were observed constructing the 3d of their animal severally and were seen laughing at the initial construction, they unpacked and constructed again trying to correct the initial mistake. They were seen sticking and re-sticking, measuring and cutting material to the desired length*
>
> *(Observation, $9^{th}$ /03/2017)*
>
> *Learning this way [iSTEMa] makes much sense, and the activities were interesting. In the activity of extracting the DNA from a living tissue we were working like (.....) real scientist*
>
> *(Saraya, Interview, $23^{rd}$ /03/2017)*

Given the findings in this sub-theme, activities such as searching for relevant ideas, sketching your ideas, defining the problem and constructing the 3d animal, seem to engage the learners' higher cognitive processes. The activities seem to make the learner active in the learning process. Thus, leading to improved genetic achievement. The findings corroborated the quantitative data presented earlier which indicated that students who learn with iSTEMa perform better than the comparative group. This could be attributed to active engagement in the learning process

## 5.17 Interaction Effects between Instructional Approach and students' ability in Critical Thinking Skills

To answer the research question 4 which states that; are there any interaction effects between high and low ability and the instructional approaches on senior secondary school students' critical thinking skills? This research question was translated into a corresponding hypothesis 3. To compare whether the two independent variables interact with each other, factorial MANOVA was conducted to determine whether there are statistical interaction effects. The dependent variable is a critical thinking skill score. The result is as presented in Table 5.38

Table 5.38

*Interaction Effects of Instructional Approaches and Students' Ability on Post-test Critical Thinking Skill score*

| Effect | | Value | F | Hypothesis df | Error df | Sig. | partial $\eta^2$ |
|---|---|---|---|---|---|---|---|
| Groups | Pillai's Trace | .21 | 5.16 | 5.00 | 92.00 | .01 | .219 |
| | Wilks' Lambda | .78 | 5.16 | 5.00 | 92.00 | .01 | .219 |
| | Hotelling's Trace | .28 | 5.16 | 5.00 | 92.00 | .01 | .219 |
| | Roy's Largest Root | .28 | 5.16 | 5.00 | 92.00 | .01 | .219 |
| Ability | Pillai's Trace | .10 | 2.16 | 5.00 | 92.00 | .06 | .105 |
| | Wilks' Lambda | .89 | 2.16 | 5.00 | 92.00 | .06 | .105 |
| | Hotelling's Trace | .11 | 2.16 | 5.00 | 92.00 | .06 | .105 |
| | Roy's Largest Root | .11 | 2.16 | 5.00 | 92.00 | .06 | .105 |
| Groups* Ability | Pillai's Trace | .11 | 2.43 | 5.00 | 92.00 | .05 | .117 |
| | Wilks' Lambda | .88 | 2.43 | 5.00 | 92.00 | .05 | .117 |
| | Hotelling's Trace | .13 | 2.43 | 5.00 | 92.00 | .05 | .117 |
| | Roy's Largest Root | .13 | 2.43 | 5.00 | 92.00 | .05 | .117 |

Table 5.38 indicates the that the main effects of ability were not significant between high and low students' ability of the iSTEMa and traditional group; Wilks' Lambda $\wedge = .89$ $F(5, 92) = 2.16$, $p = (0.06) >.05$. The partial $\eta^2 = 0.105$, indicating that 10.5% of the total variance can be attributed to students' ability.

There was no significant interaction effect between students' ability and instructional approach Wilks' Lambda ∧ = .91 $F(5, 92) = .13$, $p = (0.05)$. The partial $\eta^2 = 0.117$. Indicating that the combined effects of the instructional approach and ability were not significantly higher for the iSTEMa group than the traditional group. The partial $\eta^2 = 0.117$, indicating that only 11.7% of the total variance is accounted for by the interaction effects between instructional approach and students' ability. The test of between-subjects of all the dependent variables is as presented in Table5.39

*Table 5.39 Test of Between-Subject Effects on Critical Thinking Skills Subskills*

| Source | Dependent Variable | df | Mean Square | F | Sig. | Partial |
|---|---|---|---|---|---|---|
| Groups | Inference | 1 | 141.07 | 11.55 | .00 | .10 |
| | Recognizing Assumption | 1 | 37.48 | 3.89 | .05 | .03 |
| | Deduction | 1 | 98.92 | 7.96 | .00 | .07 |
| | Interpretation | 1 | 76.82 | 6.14 | .01 | .06 |
| | Evaluating Arguments | 1 | 43.50 | 6.19 | .01 | .06 |
| | Critical Thinking Score | 1 | 1875.46 | 25.78 | .01 | .21 |
| Ability | Inference | 1 | 2.87 | .23 | .62 | .00 |
| | Recognizing Assumption | 1 | 33.92 | 3.52 | .06 | .03 |
| | Deduction | 1 | .01 | .00 | .97 | .00 |
| | Interpretation | 1 | 79.69 | 6.37 | .06 | .06 |
| | Evaluating Arguments | 1 | .00 | .00 | .97 | .00 |
| | Critical Thinking Score | 1 | 2.60 | .03 | .85 | .00 |
| Groups * Ability | Inference | 1 | 29.24 | 2.39 | .12 | .02 |
| | Recognizing Assumption | 1 | 10.11 | 1.05 | .30 | .01 |
| | Deduction | 1 | 24.29 | 1.95 | .16 | .02 |
| | Interpretation | 1 | 19.60 | 1.56 | .21 | .01 |
| | Evaluating Arguments | 1 | 16.86 | 2.40 | .12 | .02 |
| | Critical Thinking Score | 1 | 23.75 | .32 | .56 | .00 |
| Error | Inference | 96 | 12.21 | | | |
| | Recognising Assumption | 96 | 9.61 | | | |
| | Deduction | 96 | 12.42 | | | |
| | Interpretation | 96 | 12.50 | | | |
| | Evaluating Arguments | 96 | 7.02 | | | |
| | Critical Thinking Score | 96 | 72.72 | | | |

Table 5. 39 shows the between-subject effects of the main effects of students' academic ability on critical thinking subskills of inference, recognising assumption deduction, interpretation and evaluation of arguments of the iSTEMA and traditional

group. The result indicates that there was no significant difference between the high and low ability students of iSTEMa and traditional group in all the dimensions ($p> .05$). The overall score also indicated no significant difference; $F(1, 96) = .03$, $p = (0.85) >0.05$. Therefore, there was no significant difference between the high and low ability students of the iSTEMa and traditional group

The interaction effects between the two independent variables in all critical thinking dimensions were not significant (*p >0.05).* Therefore, the null hypothesis which states that there are no significant interaction effects between students' ability and instructional strategy on selected senior secondary school students' critical thinking skills is not rejected. The interaction effects are further presented in a graphical form in Figure 5.16

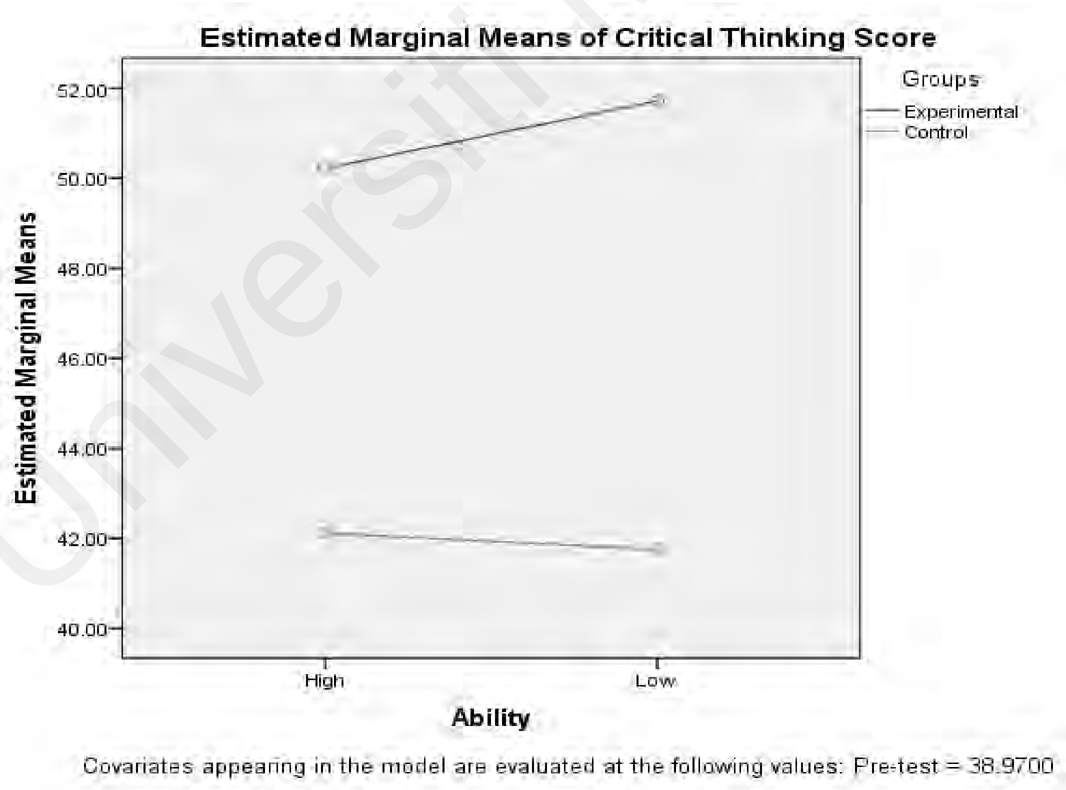


*Figure 5.16.* Interaction effects of students' Ability and Instructional Strategies

Figure 5.16 shows that there are no significant interaction effects between the instructional approach and students' ability. The results suggested that instructional approach (integrated STEM education and traditional teaching strategy) and students' ability (high, and low) did not interact in a manner that could influence critical thinking skills development among the students.

## 5.18 Interaction Effects between Instructional Approach and Students' Ability on Genetic Achievement

To answer the research question 5 which states that; are there any interaction effects between high and low ability and the instructional approaches on senior secondary school students' achievement in genetics? This research question was translated into a corresponding hypothesis 4; there are no significant interaction effects between students' ability and instructional strategy on senior secondary school students' achievement in genetics. To compare whether the two independent variables interact with each other, between subject factorial MANOVA was conducted to determine whether there are statistical interaction effects because the pre-test results of the two groups high and low ability students, The result is as presented in Table 5.40

Table 5.40

*Interaction Effects of Instructional Approaches and Students' Ability on Post-test Genetic Achievement*

| Effect | | Value | F | Hypothesis df | Error df | Sig. | Partial $\eta 2$ |
|---|---|---|---|---|---|---|---|
| Group | Pillai's Trace | .15 | 5.65 | 3.00 | 94.00 | .00 | .153 |
| | Wilks' Lambda | .84 | 5.65 | 3.00 | 94.00 | .00 | .153 |
| | Hotelling's Trace | .18 | 5.65 | 3.00 | 94.00 | .00 | .153 |
| | Roy's Largest Root | .18 | 5.65 | 3.00 | 94.00 | .00 | .153 |
| Ability | Pillai's Trace | .01 | .43 | 3.00 | 94.00 | .72 | .014 |
| | Wilks' Lambda | .98 | .43 | 3.00 | 94.00 | .72 | .014 |
| | Hotelling's Trace | .01 | .43 | 3.00 | 94.00 | .72 | .014 |
| | Roy's Largest Root | .01 | .43 | 3.00 | 94.00 | .72 | .014 |
| Group * Ability | Pillai's Trace | .07 | 2.70 | 3.00 | 94.00 | .04 | .079 |
| | Wilks' Lambda | .92 | 2.70 | 3.00 | 94.00 | .04 | .079 |
| | Hotelling's Trace | .08 | 2.70 | 3.00 | 94.00 | .04 | .079 |
| | Roy's Largest Root | .08 | 2.70 | 3.00 | 94.00 | .04 | .079 |

Table 5.40 shows that the main effects of ability were not significant between high and low students' ability of the iSTEMa and traditional group; Wilks' Lambda $\wedge = .98$ $F(3, 94) = 2.70$, $p = (0.72) > .05$. The partial $\eta^2 = 0.079$, indicating that 7.9% of the total variance is attributed to students' ability.

There is a significant interaction effect between the approaches and students' ability. Wilks' Lambda $\wedge = .92$ $F(3, 94) = 2.70$, $p = (0.04) < 0.05$. Therefore, the between-subject effects were presented to determine the source of the significant difference as presented in Table5.41.

Table 5.41

*Test of Between-subject interaction effects on Genetic Achievement*

| Source | Dependent Variable | df | Mean Square | F | Sig. | Partial |
|---|---|---|---|---|---|---|
| Group | Terminology | 1 | 63.06 | 8.15 | .01 | .078 |
| | Mendel's Laws | 1 | 81.60 | 4.49 | .03 | .045 |
| | Probability | 1 | 13.38 | 1.32 | .25 | .014 |
| | Achievement Score | 1 | 22.56 | .50 | .48 | .005 |
| Ability | Terminology | 1 | 7.95 | 1.02 | .31 | .011 |
| | Mendel's Laws | 1 | 10.48 | .57 | .44 | .006 |
| | Probability | 1 | .23 | .02 | .87 | .000 |
| | Achievement Score | 1 | 42.85 | .95 | .33 | .010 |
| Group * Ability | Terminology | 1 | 33.66 | 4.35 | .04 | .043 |
| | Mendel's Laws | 1 | 36.22 | 1.99 | .16 | .020 |
| | Probability | 1 | 3.13 | .31 | .57 | .003 |
| | Achievement Score | 1 | 3.94 | .08 | .76 | .001 |
| Error | Terminology | 96 | 7.73 | | | |
| | Mendel's Laws | 96 | 18.16 | | | |
| | Probability | 96 | 10.12 | | | |
| | Achievement Score | 96 | 45.03 | | | |

Table5.41 indicates that the main effect of treatment on students' academic ability was not significant; *p-value* is greater than .05. ($p$> .05). In all the subcategories of genetic terminology, Mendel's laws and probability. This indicates that students' ability has no significant effect when students learn using iSTEMa.

The result of interaction effects between the two independent variables in terminology subsection was $F$ (1, 95) = 7.01, $P$ = 0.04, ($P$ < .05), indicating there is a significant interaction effect. The estimated total means of high and low achievers of the traditional group 14.26 and 12.66 respectively which were significantly higher than the iSTEMa group high and low achievers 11.75 and 12.03 respectively. Indicating that the combined effects of the instructional approach and ability were significantly higher for the traditional group than the iSTEMa group. The partial $\eta 2$ = 0.052, indicating that 5.2% of the total variance is accounted for by the interaction effects between instructional approach and students' ability in terminology subsection of genetic achievement. The pre-test of genetic achievement score was the covariates and a significant predictor of the post-test score. The interaction effects are further presented in a graphical form in Figure 5.17

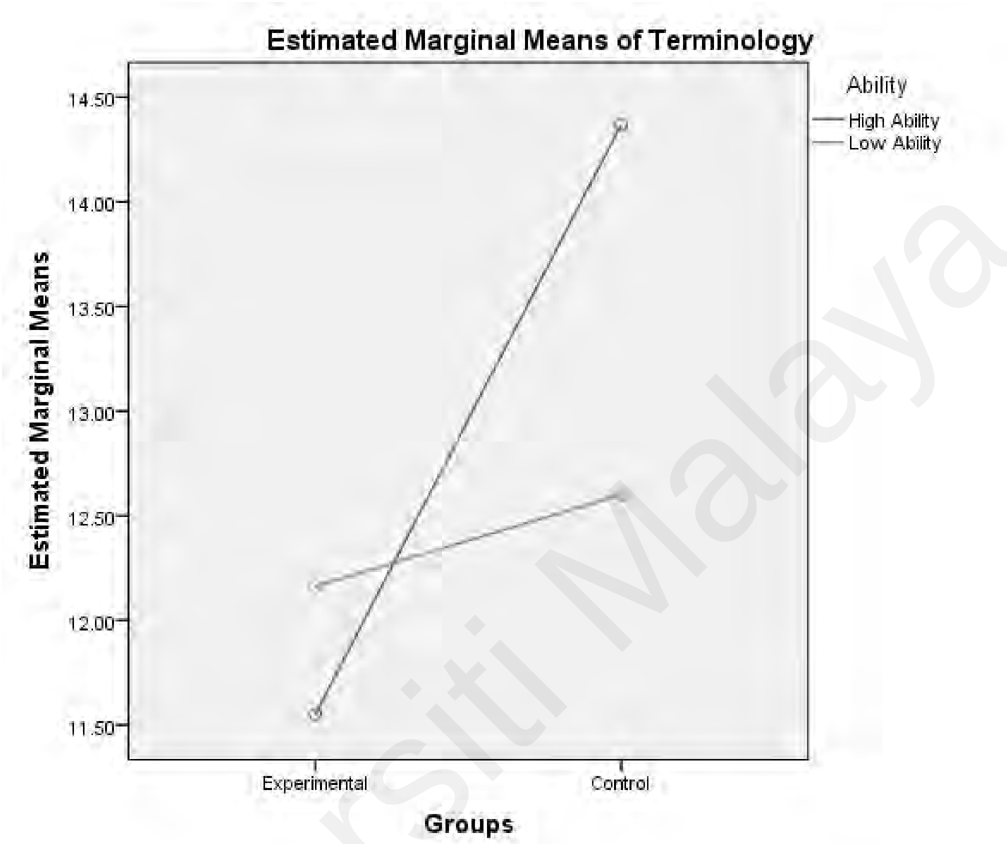


*Figure 5.17.* Interaction effects of Student's Ability and Instructional Approach for Terminology

Figure 5.17 shows that there are significant interaction effects. However, it can also be deduced that the traditional group high achievers performed better than the low achievers. On the contrary, the low achievers of the iSTEMa group have a higher mean than the high achievers. Logically, it can be concluded that the traditional learning environment tends to favour high achievers while low achievers perform comparably to high achievers in the iSTEMa learning environment.

The result of interaction effects between the two independent variables in Mendel's law and genetic probability were $F(1, 95) = 1.99$, $p = 0.16$, ($p > .05$) and $F(1, 95) = .31$, $p = 0.57$, ($p > .05$) respectively, indicating no interaction effects.

In the overall genetic achievement, there was no interaction effects between the independent variables $F(1, 95) = .08$, $P = 0.76$, ($p > .05$), $\eta 2$=0.001. The $\eta 2$ indicate only 0.1% of the total variance is accounted for by the interaction effects between instructional approach and students' ability. The interaction effects are further presented in a graphical form in Figure 5.18

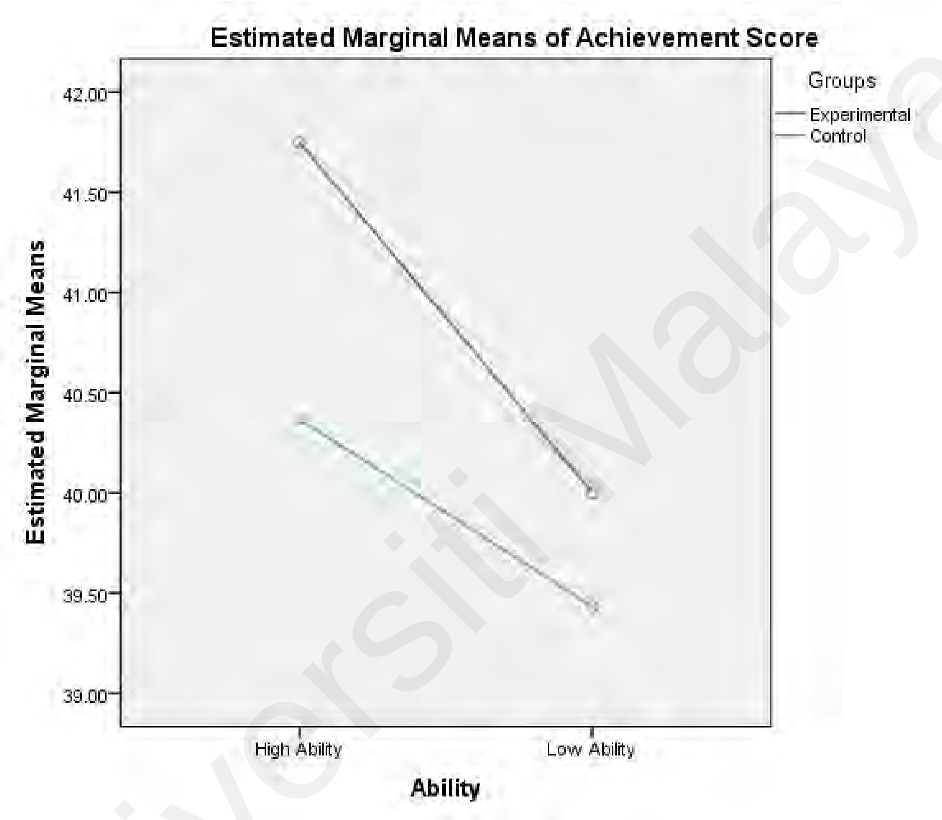


*Figure 5.18.* Interaction Effects between Instructional Strategies and Students' Ability

Figure 5.18 shows that there was no significant interaction effect. However, the means of the high and low achievers of the iSTEMa group were higher than the means of high and low achievers of the traditional group. Therefore, the null hypothesis that states that There are no significant interaction effects between students' ability and instructional strategy on senior secondary school students' achievement in genetics is not rejected. The results suggested that instructional approach (iSTEMa) and students' ability (high and low) did not significantly interact in a manner that influences overall genetic achievement among secondary school students.

## 5.19 Students' Learning Experiences with iSTEMa

Increase learning outcomes is associated with positive instructional experiences. The research question which state that; how will senior secondary school students describe their learning experiences with iSTEMa? The research question seeks to establish students learning experiences with iSTEMa. Verbal data indicated that students express their feelings and learning fulfilment which were group into two Sub-themes; learning satisfaction and disciplinary integration as highlighted below

Table 5.5.42

*Learning experience Sub-themes and definition*

| **Theme** | **Sub-theme** | **Definition** |
|---|---|---|
| Learning Experience | Learning Satisfaction | Positive or negative feelings expressed by the students |
| | Discipline Integration | Expression of efforts in the integration of STEM concepts and skills |

### 5.19.1 Learning Satisfaction

The verbal and non-verbal data described students' experiences learning with iSTEMa during and after the interventions. Students display excitement, fulfilment, approval, and joy as a learning outcome. Therefore, these expressions were captured in the theme of learning satisfaction. The students' expressions of their entire learning experience of the entire process are summarised in the following students' excerpts

> *I was involved throughout the learning process and indeed everyone in my group. Every one of us in the class was happy and joyful during the class session.*

*We try to assess or analyse and interpret specific ideas to draw an early conclusion. It was cool*

*(Aisha. Interview 24/03/2017).*

*It was exciting learning this way, and it was not dull. Learning this makes much meaning*

*(Kofiak Interview, 23/03/2017)*

*I like every aspect of the entire classroom activities, and we had fun learning this way, even those reserved in our regular classes actively participated*

*(Bege, Interview, 24/03/2017)*

*It is far better than the normal classroom teaching by the teachers, and I wish our teachers in our regular classroom could use this method of teaching*

*(Fatu, Interview, 24/03/2017)*

Students highlighted their experiences in some aspects of the iSTEMa, excerpts from students indicated that the students had thrilling experiences

*I struggle to learn in the regular (traditional) classroom, but this approach looks exciting and interesting especially going online to search for meaning and understanding, then share your thoughts with my group members*

*(Saraya Interview, 24th /03/2017)*

*In the regular classroom learning, there is always one answer that is correct and can be found in the teachers' note or textbooks, but in STEM learning you have to find a way to understand the scenario …. And established the goal of the problem =*

*= … all the students in our group approved or agreed on the right idea by assessing the whole ideas presented… it was exciting."*

*(Sheri Interview, 23/03/2017)*

It was observed throughout the exercise that students were enthusiastic and happy [smiling] during the learning session. The students were observed to actively participate in the learning process as indicated in the following excerpts

*Students could be seen showing their worksheet to each other with excitement, they argue, laugh and thump up for each other*

*(Observation, 24/02/2017)*

*Students were observed to always report very early for each class session and are seen engaging in some of the activities like searching for ideas on the internet before their classmates arrive.*

*(Observation, 24/02/2017)*

Students overall expression of learning satisfaction suggest that the students were motivated to learn using iSTEMa. Ninety per cent (90%) of the respondents during the interview expressed satisfaction learning with iSTEMa. This may have enhanced students' critical thinking skills and achievement.

### 5.19.2 Disciplines Integration

The data seems to indicate students' efforts in the integration of the discipline of science, engineering, technology, and mathematics in their quest to solve the problem. These efforts such as the application of genetic concepts, algebraic thinking, and the engineering design process are grouped under the sub-theme discipline connection or integration. The verbal data seem to indicate that the students engaged in the integration of science and engineering as highlighted in the following student's excerpts;

> *I used to think that engineering was for the construction of bridges and roads as well as the production of electronics for home use but is a problem-solving process where science and mathematics are applied. This would help me at home [daily life] to solve the problem*
>
> *(Dami, Interview 23rd /03/2017)*
>
> *I observed the connection between the discipline during the planning and designing of our mythical organism, we apply genetic principles [science] determine the probability [mathematics] of achieving the desired results and all these were possible using the integrated STEM approach [the engineering design process] (Chetnum, Interview, 23rd /03/2017)*
>
> *In the first problem, scenario uses the knowledge of dominance and recessive to prove that the trait recessive in the parents but dominant in the child. While the principles of combination [algebraic thinking] were used to establish that the trait is an inherited abnormality. We use probability [mathematics] to convince the couples with an albino child that only one out of four children will be an albino*
>
> *(Kofiak Interview, 23rd /03/2017)*
>
> *I have a feeling I can apply the STEM approach to think through a problem outside the classroom by simply defining the problem, look for ideas from science and mathematics that will help me solve the problem.*
>
> *(Aisha, Interview, 23rd /03/2017)*

Students highlighted that using this approach help them to work like STEM professionals as indicated in the student's excerpts

*At a time, I felt like I am an engineer to employ the engineering process to design a solution to our problem, I wish I were at home [student in a boarding school] where I can have access to a computer at my leisure to do more research and generate more ideas. The approach was interesting and helped me to learn science*

*(Dami, Interview, 23rd /03/2017)*

*In my regular classes, I easily forgot what I learned but applying the principles of science and mathematics to engineering looks like moving from theory to practice which help me gain more understanding of the ideas we discussed with my group members*

*(Fatu, Interview, 24th /03/2017)*

Verbal excerpts from Several students highlighted how the disciplines are connected especially during the construction of their prototype, as indicated by the following excerpts

*Drawing and creating our prototype animal or solution, help us see the connection between the scientific concept of how they are going to fit together to achieve the goal of the problem. For example, we decided the trait for skin colour from the parents should be homozygous dominant (blue colour) so that the offspring will have a dominant blue skin colour*

*(Bege Interview, 24th /03/2017).*

*For me, the approach [integrated STEM] is a way of solving the problem [thinking] which requires science and mathematics; we use it [mathematics] as probability, general rules how traits are inherited [algebraic thinking] =*

*=I observed that fork-line is a technology that helps us explain genotype and phenotypes especially dealing with the appearance of a strange trait in a family*

*(Ezenwa, Interview, 24/03/2017)*

The observation indicated that the students were using algebraic thinking to predict the genotypes of the grandparents that gave rise to the parents of the albino and the offspring as observed in Ezenwa worksheet;

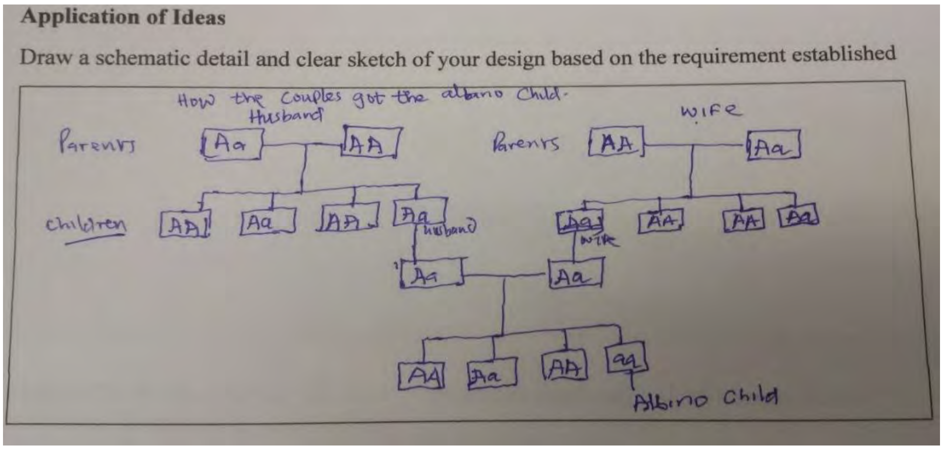


*Figure 5.19: Family Tree*

This shows a family tree and how the trait of albino was passed down to the child. It was noted that the students conclude that one of the grand-parents was heterozygous while both of the parents were heterozygous for the traits. The trait was transferred to the child. This may indicate students' critical thinking process of classifying and decoding (interpreting) information.

Given the preceding, it is inferred that the experimental students were able to learn genetics in the context of engineering and integrating the appropriate context of science, technology, and mathematics. This probably accounted for the iSTEMa group performing better than the traditional group in genetics. The iSTEMa group also did better than the conventional group in the subskill of inference, recognising assumption, deduction, and interpretation as well as evaluating information subskills of critical thinking skills. Therefore, the qualitative data supports the findings of the quantitative data presented earlier.

### 5.20 Summary of Quantitative Results

The quantitative results especially the finding from the formulated hypotheses were summarised as presented in Table 5.43

Table 5.43

*Hypotheses and Summary of Results*

| Formulated Hypotheses | Statistical Test | p-value | A decision on Null Ho |
|---|---|---|---|
| $Ho_{1:}$ There is no significant difference in the critical thinking skills between selected senior secondary school students that learn with iSTEMa and those who learn using the traditional method. | MANOVA | *P* <.05 | Rejected |
| $Ho_{2:}$ There is no significant difference in the achievement of senior secondary school students' in genetic concepts between selected senior secondary school students that learn with iSTEMa and those who learn using the traditional method. | MANCOVA | *P* (.82) <.05 | Rejected |
| $Ho_{3:}$ There are no significant interaction effects between students' ability and instructional strategy on selected senior secondary school students' critical thinking skills. | MANOVA | *P* >.05 | Not Rejected |
| $Ho_4$: There are no significant interaction effects between students' ability and instructional strategy on selected senior secondary school students' achievement in genetics. | MANOVA | *P* >.05 | Not Rejected |

## 5.21 Summary of Qualitative Findings

This subsection summarises the qualitative data analysis into the themes and subthemes that emerged from the data as presented in Table 5. 44

*Table 5.44*

Summary of qualitative findings

| **Themes** | **Sub-themes** | **Definition of Sub-themes** |
|---|---|---|
| Instructional Scaffolds | Instructional Sequence | The sequential or logical arrangement of the integrated STEM approach learning phases. |
| | Learning Clues | These are instructional guides provided to enhance the students learning and cognitive engagement |
| | Probing questions | These are open-ended questions that engage or provoke learners' critical thinking skills |
| Promote Cognitive Processing | Making Inference | Drawing an early conclusion based on available facts or information |
| | Recognising Assumption | identify a statement that is assumed to be valid and applicable or not without a proof |
| | Making Deduction | Reasoning from the general to specifics |
| | Interpretation | Students giving a brief explanation |
| | Making Evaluation | Assessing ideas and making a conclusion based on facts |
| Learning Interaction | Students' interaction | Exchange of ideas among learners with the view to achieving the learning objectives |
| | Peer Tutoring | Tutoring and co-learning among students in a group where students help each other learn |
| | Teacher-Student interaction | Learning interaction between the students and the facilitator to enhance the students learning and cognitive engagement |
| Engaging activities | Engaging activities | These are learner centred activities that engage them actively |
| Learning Experiences | Learning Satisfaction | Positive or negative feelings expressed after using iSTEMa |
| | Disciplinary integration | Expression of efforts in the integration of STEM concepts and skills |

The qualitative findings; themes and subthemes that emerged from the data is illustrated graphically as in Figure 5.20 below

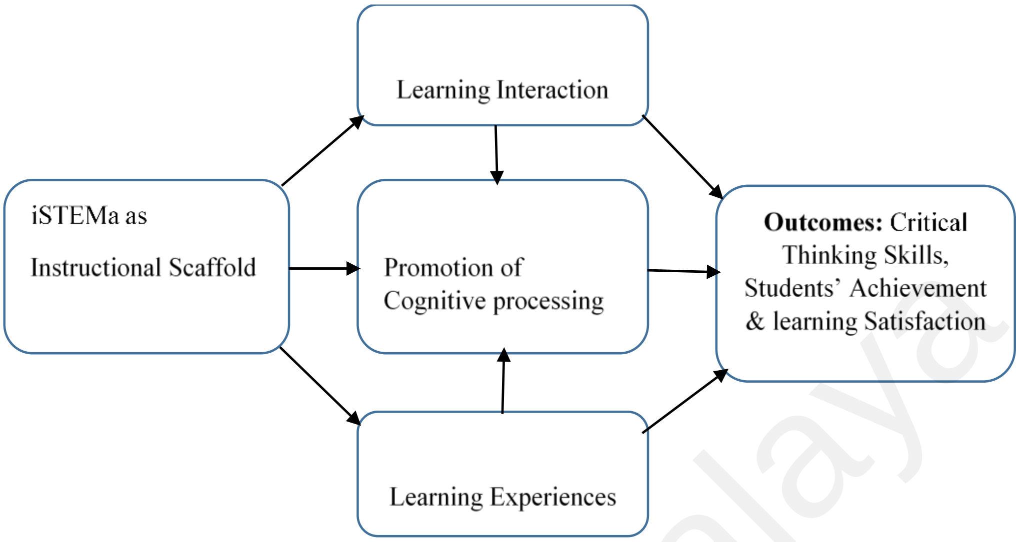


*Figure 5.20. Summary of Qualitative Findings*



The white box on the left indicates the iSTEMa and the instructional material which is made of the iSTEMa elements (open-ended problem, questioning, hands-on activities, minds-on activities) and activities which scaffold and enhanced learners' development of critical thinking skills and academic achievement. An arrow link to interaction or collaboration signifying that the instructional process characterised by social interaction which includes students brainstorming, peer tutoring among others. The elements of iSTEMa approach provided the opportunity for discipline integration. This involves the integration of the knowledge of genetics (science), probability and algebraic thinking (Mathematics) in finding a solution to the problem. The teacher interacted with the students and acts as a facilitator of the entire learning process by providing clues, question prompt, and classroom management. The discipline connection and collaboration are linked to the oval shape in the centre which indicates students’ cognitive processes; which involves processes such as justification of ideas, evaluation, analysis, querying evidence, explanation, deduction among others which are a link to students learning outcomes such as critical thinking skills, academic achievement, and learning satisfaction. The students' experiences as highlighted in the findings and are derived as students engage in higher cognitive abilities.

Therefore, iSTEMa elements, discipline integration, and interaction/collaboration are all linked to the development of critical thinking skills such as; inference, recognising assumption, deduction, interpretation, and evaluation. The data, and findings of qualitative analysis seem to indicate that students demonstrated these skills. Hence, the qualitative results corroborated the findings of the quantitative data which suggested that the approach enhanced students’ development of critical thinking skills and improved academic achievement than the traditional group. The proceeding chapter in this study will provide the discussion and conclusion of the findings.

# CHAPTER 6

# DISCUSSION AND CONCLUSION

## 6.1 Introduction

There is a consensus among scholars that critical thinking is an important goal of education and vital for academic success, workplace and life in the 21st century. It is highlighted that STEM graduates need to develop the ability to think critically and have a deep understanding of science content. Therefore, this chapter presents the summary, conclusion, and discussions of the study and how it relates to relevant literature. This was done with regards to the stated research questions and the formulated null hypotheses. The chapter also presents implications for the study, and recommendation for further studies.

## 6.2 Research Summary

The current trend in science instruction is to assists learners develop relevant skills and more in-depth understanding through integrated instruction similar to how science is practised in a real-world situation. Develop the ability to integrate knowledge from different sources to solve a problem. The trend involves the integration of critical thinking activities with science content knowledge which will equip the learner with knowledge and skills to be successful in the global society. Therefore, this research study explored the effects of integrated STEM approach (iSTEMa) on students' critical thinking skills and achievement in genetics. Students' ability was used as a moderating variable.

This study adopted a mixed method research design, and data were collected both quantitatively and qualitatively to understand better what and how iSTEMa enhanced students' critical thinking skills and achievement in genetics. To achieve the objectives of the research, an iSTEMim was prepared. The major elements of ADDIE (Need Analysis, design, development implementation, and evaluation) were adopted in preparing the iSTEMim. Science education experts validated the instructional materials for content, language, and usability. Students from the population but not part of the sample size were used to check for readability and practicability. The teacher was the facilitator in the entire learning process. The prepared iSTEMim was pilot tested and found to be valid and reliable.

The iSTEMa instructional material was implemented in secondary school, and the sample size was 100 students. This study was supported by social constructivist theory (Vygotsky, 1978). The quantitative and qualitative data were collected concurrently and analysed. The findings from the quantitative and qualitative suggest that iSTEMa is a suitable instructional approach for enhancing students' critical thinking skills and achievement in genetics among selected secondary school students. The findings of this study were summarised as follows;

1. During the preparation of the iSTEMa instructional material, Elements such as open-ended problem, real-world task, hands-on and minds-on activities, questioning, inquiry, and teamwork were embedded into the instructional materials. The phases of the approach are; engaging problem, generation of ideas, designing solution, evaluation, and communication. The instructional content was genetics and the application of genetics to bio-engineering.

2. iSTEMa was more effective in enhancing secondary school students' critical thinking subskills of inference, recognising assumption, deduction, interpretation and evaluating arguments of the students who learned using iSTEMa (experimental group) than the traditional method (control group). The

effect size of the iSTEMa group was large while that of the traditional group was small (Cohen, 1988)

3. The findings from the qualitative data corroborate with the quantitative findings on critical thinking skills where iSTEMa group perform better than the traditional group. The iSTEMim scaffolds students' learning through; instructional sequence, learning clues and prompting. It was also found that iSTEMa promotes cognitive processes namely inference, recognising assumption, deduction, interpretation, and evaluation. These qualitative findings seem to substantiate the quantitative findings.

4. iSTEMa also improved students' achievement in a genetic subsection of terminology, probability and Mendel's laws than the traditional teaching method. The mean difference between the iSTEMa and traditional group was not significant in terminology, probability, and the overall genetic achievement score. However, there is a significant difference in Mendel's laws subsection in favour of the iSTEMa group. The mean gained of the iSTEMa group was higher than the traditional group in the overall result, suggesting that the iSTEMa learning environment was more effective than the traditional learning environment

5. The emerging themes from the qualitative data to collaborate the quantitative findings (iSTEMa group performs better than traditional group) on genetic achievement were learning interaction (students and student, peer tutoring and teacher and student interaction) and engaging activities.

6. The findings show that there is no interaction effect between instructional strategies and students' ability in critical thinking skills. Hence, students' improvement in critical thinking skills can be attributed to the effects of the

instructional approaches used. Student ability is an essential factor to consider when planning instruction; the researcher considered the main effect of student ability as a moderating variable on critical thinking skills. The findings indicated that both high and low abilities of the iSTEMa group improved in their critical thinking skills more than the traditional learning group in inference, recognising assumption, deduction, interpretation and evaluating arguments. The mean score was significant in favour of the high and low achievers of the iSTEMa group, and the low achievers have the highest mean. Hence, this suggests that iSTEMa approach to learning help to reduce the achievement gap between high and low achievers.

7. The findings also indicate that there is no interaction effect between instructional strategies and students' ability in the genetic subsection of probability, Mendel's laws and overall genetic achievement. However, there were interaction effects in genetic terminology subsection. Hence, students' improvement in the overall genetic achievement can be attributed to the effects of the instructional approaches used. The main effect of student ability as a moderating variable on genetic achievement indicates that the high and low achievers of the iSTEMa have higher means than the traditional group. However, the mean difference was not significant between high and low achievers of the iSTEMa and traditional group.
8. The students' participants described their learning experiences with iSTEMa which was grouped into learning satisfaction and discipline integration. The students expressed joy and satisfaction learning with iSTEMa.

## 6.3 Conclusion and Discussion

Literature has highlighted the need to assists secondary school students to acquire and apply critical thinking skills (Kivunja, 2015; Teo, 2019). On the other hand, the integrated STEM approach is perceived as an effective approach to enhance the meaningful understanding of science and mathematics as well as enhance critical thinking skills (Lay & Osman, 2018; National Research Council, 2012). However, there is no substantial literature linking integrated STEM approach with critical thinking skills and academsic achievement in genetics. Therefore, this study investigated the effects of iSTEMa on senior secondary school students towards critical thinking and academic achievement in genetics. From the findings of this study, four main conclusions were drawn;

1. Integrated STEM approach (iSTEMa) enhanced critical thinking skills among selected secondary school students. The elements of iSTEMa engaged students' higher cognitive abilities which may have led to the enhancement of critical thinking skills
2. The iSTEMa enhanced students' achievement in genetics among selected secondary school students. The elements of integrated STEM approach (iSTEMa) engaged students actively through students' interaction, group project and peer tutoring promoted students' achievement in genetics.
3. Integrated STEM approach (iSTEMa) improved high and low achievers critical thinking skills. It is appropriate for both high and low achievers learning
4. The high and low ability of the iSTEMa group performs better than the high and low ability of the traditional group. The iSTEMa learning environment is suitable for students learning of high and low academic abilities in genetic achievement.

5. The iSTEMa group demonstrated learning satisfaction and disciplinary integration in the iSTEMa learning environment. It is logical to conclude that iSTEMa learning environment is favourable for science instruction among secondary school students. These conclusions were discussed in detail as presented below.

### 6.3.1 iSTEMa Enhanced Critical Thinking Skills

One of the vital purposes of education is to help learners acquire critical thinking skills (Facione, 2011; Tiruneh et al., 2018; Zulmaulida et al., 2018). It was advocated that critical thinking learning should be learned in a specific subject domain (Bensley & Spero, 2014; Saputri et al., 2019). Therefore, the processes of critical thinking skills; inference, recognition of assumption, deduction, interpretation are more related to the essence of classroom instruction. In this study, the iSTEMa provided the latitude to engage in these cognitive processes. The elements, components, phases, and activities in the iSTEMa instructional material could have mediated the improvement of critical thinking skills.

The students demonstrated the ability to infer, recognised assumption, deduce, interpret and evaluate. This finding concurs with previous literature which reported that students' engagement in integrated STEM-based approach enhanced critical thinking skills in science (Duran & Sendag, 2012; Oonsim & Chanprasert, 2017; Phonchaiya, 2014; Saputri et al., 2019). For example, Oonsim and Chanprasert (2017) in their study, the development of critical thinking skills by STEM education among $11^{th}$-grade students in physics (electrostatic). The findings indicated a 49% increase in students' critical thinking skills. Similarly, Phonchaiya (2014) reported that instructional activities that are organised in a STEM-based instruction improve learners' development of critical thinking and problem-solving abilities. Researchers have reported improved critical thinking skills among secondary school students globally in domain-specific evaluation (Nuswowati & Purwanti, 2018; Tiruneh et al., 2017). For instance (Tiruneh et al., 2017) found enhanced students' critical thinking skills in electricity and magnetism using Critical Thinking Test in Electricity and Magnetism (CTEM). This finding also concurs with several previous studies which reported that critical thinking is best learned through problem-solving in a specific subject content instruction (Abrami et al., 2015; Bensley & Spero, 2014; Halpern, 2014).

This finding could be attributed to how students learn using iSTEMa. Firstly, critical thinking does not take place in a vacuum but must be stimulated. Bybee (2010) advocated that STEM education instruction should be built around a problem scenario (such as frontiers of STEM, example genetic modification) that will require students to integrate STEM concepts and principles to solve and through that students will acquire skills like critical thinking. Therefore, to help learners develop critical thinking skills, there is the need for a mental challenge that will engage learners' ability to infer, deduce, recognise assumption, interpret and evaluate. In this study, an engineering design open-ended challenge was therefore presented in the iSTEMa instructional material. The open-ended problem is characterised by complex information and consist of several ways to address the problem. Cox et al. (2016b) reported that an open-ended problem provides the students with several options and leeway through which to address the problem. For example, in the present study, one of the problem scenarios, students are requested by a sale's representative to engineer a unique Savannah Hare that will benefit society. Therefore, students' higher cognitive ability is stimulated to view the problem from several possible perspectives. This problem encourages students to develop several ideas to establish what is unique and its benefits to the society. Thus, engaging students' higher cognitive processes to invent a feasible solution to the open-ended problem. The word unique in the problem scenario mainly makes the problem very open because students will view unique from several perspectives; size, economic value, aesthetic value among others. This suggests that the open-ended problem in this approach could have stimulated learners to think critically through deduction, interpretation, evaluation, and inference.

The students were also involved in engaging the problem (first phase of iSTEMa) through considering the relationship among different components of the open-ended problem and based on these components the goal of the solving the problem is highlighted. The learners considered the facts about the problem and based on the facts speculate the goal and constraints of solving the problem. Thus, engaging in deductive thinking skills by reasoning from the general problem to a specific goal. The ability to draw early conclusions based on available facts about the problem suggest students engaging in inference. These findings agree with Watson and Glaser (2010) in the revised Watson and Glaser critical thinking appraisal II highlighted defining the problem as part of the deductive skills of critical thinking. The qualitative result indicated that learners actively engaged in the learning process through minds-on and hands-on activities; learners engage in experiment and group project. This also concurs with DeJarnette (2012) who reported that instructional activities that will foster critical thinking skills should include active engagement and problem-solving.

This finding is buttressed by the earlier findings of Carvalho et al. (2015) and Cox et al. (2016b) who reported that one of the important approaches to enhance students' critical thinking skills is to engage them in solving the real-life open-ended problem. Similarly, Douglas et al. (2012) reported that to promote critical thinking skills, learners are required to explore real-life open-ended problems.

Nonetheless, the open-ended scenario was not the only likely factor for critical thinking improvement of the iSTEMa group. The enhancement of critical thinking skills was also possible through the integration or application of mathematics through algebraic thinking, probability, and engineering design process. The students also utilised technology tools to get information on genetics and procedures for genetic engineering to design a solution. During STEM integration, students do not only acquire knowledge and skills but apply the knowledge and skills to develop a solution. The process of acquiring knowledge and the application of this knowledge to problem-solving could have also helped learners engage in evaluating a large amount of information encountered and deciding the relevant information (recognising assumptions) to the goal of the problem. Thus, engaging in the evaluation, interdisciplinary experience and recognising information. This concurs with Jones (2012) who reported that instructional approaches that provide interdisciplinary experience involving problem and design-based learning significantly enhance students' critical thinking skills

The positive findings could also be as the result of iSTEMa and critical thinking elements such as questioning. The ability to think critically was also mediated by questioning, students through questioning probe each other ideas, thoughts for evidence and justification. These questions where eminent while defining the problem and during the generation of ideas. The Students prompt each other with questions such as *what do you mean?* (seeking explanation and clarification). This finding agrees with Kalelioğlu and Gülbahar (2014) where they reported that students' critical thinking is enhanced when students engaged in Socratic questioning which facilitates exchange and evaluation of thoughts. The finding is also supported by Corley and Rauscher (2013) who said in their report that higher-level questioning enhances students' ability to think critically. They further explain that higher order questions encourage explanations, clarification, evaluation and encourage students to ask divergent questions (Corley & Rauscher, 2013).

Scholars have recommended the use of collaboration as a strategy to foster critical thinking skills among students (McCrae, 2011; Nathan, 2010). The iSTEMa was structured such that students work individually to generate ideas or relevant information, about the problem and meet in a small group to discuss their ideas. During the collaboration, students present and defend their ideas engaging in interpretation and justification of their ideas. Students listen to each other carefully, appreciate their opinions or views and prompt for clarification. (students in the process gain communicative and collaborative skills). The group first identify and assess the ideas that are applicable and draw a conclusion on the best idea, thus engaging in evaluation and inference subskill of critical thinking. This result agrees with scholars who reported that collaboration or teamwork enhance critical thinking skills, especially when learners collaborate to solve an open-ended problem (Crenshaw, Hale, & Harper, 2011; McCrae, 2011). This also agrees with the findings of Loes and Pascarella (2017) who reported a strong link between collaborative learning and students' acquisition of critical thinking skills.

The teacher plays a critical role in the learning process through facilitation which was not being expected. The qualitative data indicated the teacher and students' interaction during collaboration, hands-on activities, exploration, and a group project. These were effectively achieved through the use of several techniques by the teacher such as question prompts, learning clues and open-ended scenario to scaffold meaningful learning. Thus, teacher facilitation seems to have contributed meaningfully to enhance students' critical thinking skills. This finding collaborated the results of Seimears, Graves, Schroyer, and Staver (2012) who reported that teachers could achieve effective facilitation through the use of several techniques; questioning and exploration of open-ended problems to enhance conceptual understanding. This was also supported by the earlier findings of (Asyari et al., 2016; Batdı, 2014; Carvalho et al., 2015; Lay & Osman, 2017).

### 6.3.2 iSTEMa Enhanced Genetic Achievement

This study also investigated the effects of iSTEMa on the genetic achievement of selected secondary school students. The result was not as expected because the mean difference between the iSTEMa group and the traditional group was not significant in the overall result. However, the iSTEMa group mean was higher than the traditional group. Therefore, it was concluded that iSTEMa was more effective in enhancing students' achievement in genetics among the sample of the population than the traditional method.

This result concurs with previous findings of researchers in STEM-based approach. (English et al., 2013; Fortus et al., 2005; Guzey et al., 2017b; Robinson et al., 2014; Thomas, 2013; Zhbanova et al., 2010). Robinson et al. (2014) carried a study compares the performance of students in a standardised test between students who participated in a STEM intervention programme for starters and the control group (non-STEM intervention group). The findings of the research revealed that science process skills and science content knowledge of the experimental group were significantly higher than the comparative group.

Similarly, Guzey et al. (2017b) who conducted a case study on life science learning using engineering in K-12, a pre and post-test design was adopted. The findings showed higher gains in science and engineering concepts. The results of the study also agree with some policy documents that recommended the integration of engineering as engineering design process into science instruction at the secondary school level (Ministry of Education, 2013; National Research Council, 2012; the NGSS Lead States, 2013). The findings of this study concur with English and King (2015) and Fantz and Grant (2013) who determined the achievement of students in science content using integrated STEM using the engineering design process. The findings indicated that the STEM-based group performs better than the traditional group.

On the contrary, the findings did not concur with James (2014) who investigated the extent of STEM education influence on mathematics and science achievement among seventh-grade students. The quantitative method of data collection was adopted; an independent *t*-test was used to analyse the data. The result showed that the traditional mathematics and science group (control) perform significantly better than the iSTEMa group. It was concluded that the STEM programme in that given population was not associated with higher science and mathematics achievement. Similarly, Han, Rosli, Capraro, and Capraro (2016) discovered that STEM Project-based learning did not improve students' science achievement.

The positive result of this present study could be attributed to the learning environment provided by the iSTEMa through learning opportunities where students search for genetic information, engage in hands-on activities to simulate how traits are inherited. This may have facilitated students' conceptual understanding of genetics and its application to problem-solving. The higher mean score of the iSTEMa group could also be attributed to the students involving in cross-disciplinary and solving open-ended problem that requires the application of genetic knowledge in the context of other disciplines.

This concurs with Estes, Gunter, and Mintz (2010) opined that exploring within-discipline big idea facilitates content understanding through design strategies. This finding also agrees with Czerniak and Johnson (2014) who opined that integrated learning enhanced students' content knowledge of subject matter and motivated the learners to engage in meaningful learning. Daugherty 2012 reported that entrenching open-ended science problem in a design-based learning approach enhanced the meaningful learning of science through exploration, scientific inquiry, and developing a solution to the problem.

For meaningful learning to take place, the new knowledge must be compatible with prior knowledge. In this study, the question "*what you know about the problem?*" during the engaging problem will engage and activate student prior knowledge which is vital for meaningful learning to take place. This concurs with Fahim and Masouleh (2012), and Kim et al. (2013) who reported that good questioning might serve as scaffolds to provide students with the opportunity for more profound thought and enhance students engagement in learning.

The performance of the iSTEMa group can also be attributed to the students' manipulation of material. For example, the students simulated the inheritance of traits by offspring from their parents. The students also applied content knowledge of genetics (science), probability and algebraic thinking (mathematics) by deciding which alleles is dominant and recessive during problem-solving. That is, the student applied their content knowledge of genetics and mathematics to develop a solution to the open-ended problem (engineering a unique hare that will benefit the society) using available resources. Hansen and Gonzalez (2014) findings in a related topic; the relationship between STEM instructional principles and achievement in mathematics and science among students. They concluded that STEM-based instruction has a positive association with students' achievement in mathematics and science.

STEM-based instruction was characterised by group project and hands-on activities which could have contributed to students' meaningful learning of science content (Olivarez, 2012). Therefore, in iSTEMa, students' engagement in a group project by modelling how a trait from the parents will combine to become dominant or recessive in the offspring. This may have accounted for the significant difference between the two groups in genetic laws in favour of the experimental group. The findings indicated that the students engage in peer tutoring; with the learners taking alternate roles between tutor and tutee to explain to each other and share their genetic knowledge. This help to increase learners' interaction and help them to engage actively in the learning process. This concurs with Gok (2012) determined the impacts of peer instruction on students' conceptual understanding and belief in physics using the quantitative method. The findings showed that the peer instruction and problem-solving group had a better conceptual understanding than the related group. On the overall, the result concurs with the earlier findings of Olivarez (2012), Sahin, Ayar and Adiguzel (2014) and Thomas (2013) who reported increased in students' achievement when students were instructed with integrated STEM-based approaches

Some of the findings were not being expected because of the potential of STEM instruction to improve students learning outcomes. For instance, the result shows that the mean difference between the iSTEMa and the traditional group was not significant for the terminology and probability subsection of genetics as well as the overall academic achievement in genetics. The reason for the lack of significant difference can be attributed to students lack prior experience in STEM-based learning, and this could have affected the ability of the students to balance content learning with engineering designed-based activities. Another reason could be because of the paradigm shift in instructional practice from outcome-based learning to process-based learning which could have impacted science content learning. Therefore, this can be inferred that the change in learning approach requires enough time and consistency for students to achieve a significant difference in science content achievement. This assertion is supported by Apedoe and Schunn (2012) who reported that strategies associated with designed-based learning might not necessarily be associated with success in science content learning. Since iSTEMa is process oriented, the standardised test may not have also been appropriate for evaluating students' achievement in genetics. This assertion is corroborated by the finding of Johnson and Christensen (2012) who reported no significant difference between STEM-based school and non-STEM based school students' achievement in science and mathematics among secondary school students.

### 6.3.3 Critical Thinking among High and Low Ability

Providing instructional strategies and environment that caters for learners with different abilities to provide learning equity has been advocated (Prayitno et al., 2019; Thalib et al., 2017). Therefore, the need for schools to bring all students up to the minimum proficiency level. To achieve this, instruction must be tailored towards their individual needs and adequate instructional support should be carefully selected to meet these individual needs or differences (McDonald Connor & Morrison, 2016). Similarly, Thalib et al. (2017) accentuated that students' abilities are a vital factor that impacts students' learning. The study seeks to find the main effects of students' ability on students' critical thinking.

It was concluded that high and low achievers of the iSTEMa group perform better than their traditional group counterpart in their critical thinking skills, the high and low achievers of the iSTEMa group gained from the treatment. However, the low achievers of the iSTEMa group performed better than their high achievers' counterpart in critical thinking skills. The low achievers of the iSTEMa group had the highest effect size. This suggests that iSTEMa learning environment is suitable for students' learning with different abilities. This confirms the earlier assertion that instructional approaches that are learner-centred and characterised by deduction improve both high and low ability students' critical thinking skills(Prayitno et al., 2019).

This finding concurs with the findings of Yu et al. (2010) who reported that low achievers perform better than high achievers using non-traditional approaches. This suggests that low achievers perform well compared to their high achiever's counterpart in higher order thinking task which will positively impact the learners' critical thinking skills. Thalib et al. (2017) who reported that low achievers perform better than high achievers in critical thinking skill using Reading Questioning and Answering (RQA) instructional strategy.

The iSTEMa is characterised by inquiry activities; conducting experiments, formulating hypotheses, analysing data and communication of findings. These activities may have enhanced students' cognitive processes leading to improve critical thinking skills as indicated in the qualitative data. This finding agrees with some scholars who opined that instructional strategies characterized by analysing information, questioning, conducting experiments, draw conclusion and communication of findings improve the learning needs of low, medium and low achievers (Ibrahim, Aulls, & Shore, 2016; Kulo & Bodzin, 2012; Kuo et al., 2018). Kuo et al. (2018) employed inquiry-based instruction to explore low achievers' motivation towards learning science among 8th graders. Elements of active engagement characterised the approach; proposing questions, formulating hypotheses, designing experiment, drawing conclusion and communication of findings. The findings show that low achievers' learning outcomes and the value of science learning were improved.

The social constructivist environment may also have provided the scaffold for low achievers to engage in cognitive activities through interaction with high achievers. For example, in the traditional class, the students were less engaged because the learning process was teacher-centred, on the contrary, the iSTEMa group actively engaged because the learning process was student-centred, while the teacher acts as a facilitator. This could have enhanced the ability of the students to think critically. This concurs with Taber (2010) who highlighted that instruction based on social constructivist theory suits classroom instruction of students with different abilities.

The qualitative data shows that low achievers were not passive but actively engage like high achievers in the learning process, suggesting that low achievers also contributed to the learning task regarding ideas, brainstorming and a group project. Thus, engaging in evaluating ideas, deductive thinking, and application of genetics concept among others. These could have enhanced students' critical thinking skills. This concurs with Yang, Van Aalst, Chan, and Tian (2016) found that students with low academic ability benefited from collaborative knowledge building. This suggests that instructional strategies that actively engage the learner and are characterised by collaboration tend to enhance low achievers' learning outcome.

This finding is contrary to the assertion by teachers that low achievers may not cope with critical thinking skill task (Marin & Halpern, 2011; Schulz & FitzPatrick, 2016). Low achievers engagement in the iSTEMa iterative learning process (reflecting on previous phases) seems to provide the support for low achievers to think critically. Petroski (2010) reported that the engineering design process has many phases where stops are essential, and learners move forth and back to achieve the goal of the design task. In this study, the iterative cycle begins with engaging the problem, and the last phase is the communication of findings. The iterative nature of engineering design could have stimulated deductive and abductive reasoning; generation of several likely solutions to the problem which could have enhanced critical thinking skills (Jøsang, 2008). The iterative nature of the iSTEMa and the task embedded provided the opportunity for students to think critically as they engage in the entire learning process. The iSTEMa worksheet could have helped to enhance students' achievement of high and low ability group. The worksheet contains open-ended question, activities and assessment question which could be used individually and collectively in a group. This is supported by Romli et al. (2018) in their study, where they reported that worksheets design with an open-ended question would motivate students to find a solution to the questions Using qualitative data collection, the finding shows that instructional materials like open-ended worksheets enhance students thinking skills and improves students' performance in scientific concepts. Yildirim et al. (2011) investigated the effects of worksheets on students' achievement on the factors affecting equilibrium. Quantitatively and qualitatively data was collected. The finding shows that the treatment group (students that learned using worksheet) perform better than the comparative group

### 6.3.4 Genetic Achievement and Students' Ability

The result indicated that both the iSTEMa group and the traditional group high and low ability students gained from treatment. However, the iSTEMa learning environment was more effective in improving the achievement of high and low ability students more than the traditional learning environment. The low achievers of the iSTEMa group have the highest mean gain suggesting that iSTEMa is more suitable for both high and low achievers' science learning.

This finding agrees with the earlier findings of (Han et al., 2014; Thalib et al., 2017; Yu et al., 2010). Han et al. (2014) investigated the effects of STEM project-based learning on the performance of students with different learning abilities. The findings showed that low achievers perform better than high and medium achievers in mathematics. Yu et al. (2010) determine the effects of web and non-web-based problem-solving approach and low and high academic ability on the achievement of students in biology and problem-solving ability. The findings indicated that low achievers did better than high achievers in a non-traditional approach (open-ended problem solving). On the contrary, the findings did not concur with some findings of previous studies which indicated that high ability students perform better than the medium and lower ability students in mathematics (Gambari et al., 2013a; Raes et al., 2013).

The grouping of the students in this study was heterogeneous for ability, and gender. In heterogeneous grouping low achievers' learning was scaffold by high achievers; on the other hand, the high achievers improved their content learning, and cognitive skills through explanation and justification of their ideas. Small group learning enhanced individual members accountability and interdependence from one another (indicating the students need one another) and mutual benefits. This was highlighted in the qualitative data where students collected ideas from every member of the group, and together the group assesses the ideas to reach an agreement. In support of this, literature reported that learning environment characterised by small group learning revealed both academic and social benefits (Cheng et al., 2008; Gambari et al., 2013a). The finding corroborated the assertion of Olszewski-Kubilius (2010) accentuated that STEM education approach to instruction is more appropriate and effective for classroom instruction with mixed academic abilities.

Therefore, the main features of this iSTEMa are learners' active engagement in the learning process through minds-on, hands-on activities and teamwork, which are learner-centred. These elements could have created a conducive learning environment for both high and low achievers of the experimental group, especially for the low achievers who have the highest effect size. This, therefore, suggest that instruction characterised by teamwork, and hands-on activities promote low achievers' active engagement in the learning process leading to improve academic achievement. This agrees with previous literature that collaboration, hands-on, and minds-on activities make abstract genetic processes concrete, thereby improving students' academic performance in genetics (Grumbine, 2006; Mandusic & Blaskovic, 2015; Monvises et al., 2011). The findings of this study concur with Kwan and Wong (2015), and Thomas and Anderson (2014b) who held that learning approaches that create and promote learner-centred and active engagement (constructivist) environment enhance students' ability to engage in knowledge construction by themselves

The reason for the finding could also be attributed to group project work which provides the opportunity for students to complement each other which was beneficial to both high and low abilities and especially low ability students. This agrees with Kajamies, Vauras, and Kinnunen (2010) in their study reported that instructional approaches characterised by problem-solving and group work were suitable for learning among students with different abilities. Yang et al. (2016) observed that gaining knowledge where students take responsibility for sharing their knowledge or ideas in a supportive and collaborative knowledge building context is motivating for low achievers.

## 6.4 Implications of the Study

The Finding of these result answered the research questions and achieved the objectives of this study. These findings and the impact of this study have several significant implications; therefore, the researcher highlighted the impact this study may have on the methodology, theory, instructional practice and teacher development. These are highlighted in the next subsections

### 6.4.1 The implication to the learning Theory

With regards to the theoretical framework in this study, the constructivist theory and cognitive development theory were adopted to enhanced learners critical thinking skills and academic achievement. To achieved this, students must be exposed to appropriate instructional approaches and learning environment. The social constructivist theory linked iSTEMa and critical thinking skills and achievement. The elements of the theory that provided the latitudes or connection were active engagement, student centred learning and the social construction of ideas. The elements embedded in iSTEMa were selected based on the components of the Vygotsky theory which has enhanced learners critical thinking skills.

The gap this study has filled was to create a satisfactory learning experience that enhanced students' critical thinking skills and academic achievement using iSTEMa. This approach emphasised minds-on activities through cognitive processes such as defining problem, generation of ideas, reflection, analysis, and justification of ideas. Consequently, students' learning experience was characterised by active engagement, learner-centered instruction, and teamwork. These may have enhanced students' critical thinking skills and academic achievement. The results of this study are supported by the earlier finding of Kim et al. (2013) who found that active learning characterised by small group learning enhanced students' critical thinking skills. This concurs with the findings of other scholars who reported that the theory of constructivism directly supports high cognitive task leading to the development of critical thinking skills (Blaik-Hourani, 2011; Boden, 2010; Prayitno et al., 2019).

Another fundamental aspect of the theory is scaffolding of learning at the zone of proximal development from lower thinking skills (recall and understanding) to higher skills or critical thinking skills such analysis, evaluation, and synthesis. The ill-structured problem and real-world problem, questioning and the iterative instructional phases scaffolded learners' critical thinking skills and achievement. For example, the design problem was a challenging task in the form of an open-ended problem which could have scaffolded critical thinking skills.

Theory of constructivism provided the support for hands-on and minds-on activities which are an integral part of iSTEMa. Through these activities, learners are actively engaged in the learning process. (Lamanauskas & Augienė, 2015). They reported that critical thinking is enhanced when learners engage in minds-on activities such as justification of their ideas, drawing inferences from available data and evaluation which are fundamental aspects of scientific research. The constructivist learning environment is seen as the most suitable learning paradigm for 21st-century learning and skills (Thomas & Anderson, 2014a). Hence this theory supports the students' learning experiences in this study.

### 6.4.2 Methodological Reflections

Mixed method design was adopted to determine the effects of iSTEMa on students' critical thinking skills and achievement in genetics. One of the important strengths of this study was a collection of both quantitative and qualitative data. The quantitative data was used to determine the effects of iSTEMa on critical thinking skills and achievement in genetics. While the qualitative component involved the exploration of how learners acquire critical thinking skills and their learning experiences with iSTEMa. Therefore, the justification for adopting a mixed method was supported by the purpose of the study, which was more suitable to seek answers to the research questions rather than a single strand of quantitative or qualitative alone. This approach to research provide the latitudes for the researcher to use the findings of the secondary strand (in this study qualitative) to buttress or enhance the understanding of the primary data findings (in this study, quantitative) to achieve the purpose of the research (Creswell & Clark, 2011; Klassen et al., 2012)

One of the significant contributions was the participation of STEM experts in the preparation of the iSTEMim. The experts validated the iSTEMim and made valuable contributions to the preparation of the instructional materials. Another critical dimension of the study is that all experts were contacted via emails to participate in content validity as well as fill the validity form. Thus, the experts are mindful that Nigeria is also interested in being part of the global reform in STEM education which could create synergy in future between STEM education researchers in Nigeria and other parts of the world. STEM education research is at its embryonic stage in Sub-Saharan Africa, particularly in Nigeria. Therefore, this research could provide leeway for future research especially in Design and Development Research (DDR) in STEM education.

### 6.4.3 Implication to Instructional Practices

The iSTEMa has proved to be an essential tool for improving students' learning outcomes as indicated in the findings of the study. Specifically, the outcome of this study indicated that iSTEMa may be especially useful in senior secondary school and probably other levels of education.

The societal changes in the 21st century require the education system to adapt its instructional practices to meet these changes. This can be achieved through a paradigm shift from memorisation and learning STEM subjects in isolation to iSTEMa that include elements of critical thinking skills. Juliani (2015) and Teo (2019) advocated that teachers should purposefully design instruction to include skills that will prepare learners for the labour market demand such as critical thinking skills. The findings of this study will provide a significant change in instructional practices for educational stakeholders to critically examine their instructional practices and adopt iSTEMa as an instructional practice that will meet the present labour market needs of the 21st-century.

Integrated STEM approach environment is learner centred. Consequently, the approach can be employed by teachers to encourage self-regulated learning, help learners develop critical thinking skills and deepen learners understanding of the instructional content. Reforms in science education have advocated for a paradigm shift from the traditional instructional environment to the constructivist learning environment (Kivunja, 2015). Hence the need to develop instructional materials that are constructivist based given the scarcity of instructional guidelines to implement STEM-based instruction. Therefore, the instructional material developed for this study provides essential guides for teachers to develop relevant instructional materials and framework. Classroom instructors should seek to transform their instruction into a learning environment and experiences that nurture interdisciplinary learning.

The iSTEMa fosters interdisciplinary instruction by providing students with real-world experiences and skills that will be applied to a real-life situation. Consequently, the need for policymakers and curriculum developers to design policies that will support integrated instruction that is characterised by real-world context into the curriculum. This could prepare and equip students with skills (critical thinking skills) required for the $21^{st}$-century workforce and problem-solving

Given the outcome of this study, there is an urgent need for the departure of writing textbooks with contents and problems to be solved in silos to writing textbooks in an integrated context by STEM authors. The nature of the problems in textbooks that focus on specific discipline context and closed-ended instead of open-ended that will require the integration of knowledge and skills from other STEM disciplines. Therefore, the outcome of this study will provide an insight to authors on the need to present STEM learning content and problems to be solved similar to the way professional solve the problem in real-life.

The findings of this study also show that iSTEMa can be an effective instructional approach to enhance students' critical thinking skills and science content achievement at the secondary school level and it is appropriate for the learning of students with different abilities. Research on integrated STEM-based instruction and students is inconclusive (Shernoff, Sinha, Bressler, & Ginsburg, 2017) Therefore, this study has contributed to the existing literature on STEM-based learning.

## 6.5 Recommendation for Further Research

As reported in chapter 1, the study was limited to senior secondary school students of federal government colleges in Niger state, Nigeria. Therefore, caution should be taken in the interpretation and generalisation of the findings to all senior secondary school students in Niger state. For further research, a longitudinal study of this research can be carried out from the nursery through primary and junior secondary school students. To determine the long term impacts of STEM-based approach on students learning and critical thinking skills.

Tiimner, Chapman, Greaney, and Prochnow (2002) observed that factors such as duration of research intervention, time allocated for each lesson and the frequency of the lesson per week/month. These factors may affect the learning outcome of a study. In this study, the learning duration was eight (8) weeks, and the frequency of the lessons was twice a week. Therefore, it is recommended for a more extended intervention in future studies. Further research can be carried out with other students at different educational levels such as; pre-service teachers, and engineering students to establish whether the results of this study can be generalised on other research populations.

There are limited studies on teachers' classroom experiences with integrated STEM approach (Dare et al., 2018). Therefore, further research could be undertaken to focus on teachers' classroom experiences with integrated STEM approach. This may provide a holistic understanding of teachers and students' classroom experiences with integrated STEM education.

The sample size of this was one hundred (100) students. Therefore, it is recommended that a more significant number of a sample size could yield meaningful data and findings in future research. Qualitative research can also be carried out to explore in detail students learning with iSTEMa especially at the secondary school levels with other variables like students' gender, school location, and socioeconomic status. The research could also focus on teachers' professional development in integrated STEM-based instruction.

## References

Abdu-Raheem, B. O. (2014). Improvisation of instructional materials for teaching and learning in secondary schools as predictor of high academic standard. *Nigerian Journal of Social Studies, XVII*(1), 131-143.

Abrami, P. C., Bernard, R. M., Borokhovski, E., Waddington, D. I., Wade, C. A., & Persson, T. (2015). Strategies for teaching students to think critically: A meta-analysis. *Review of Educational Research, 85*(2), 275-314.

Abualrob, M. M. A., & Daniel, E. G. S. (2013). The Delphi technique in identifying learning objectives for the development of science, technology and society modules for Palestinian ninth grade science curriculum. *International Journal of Science Education, 35*(15), 2538-2558.

Acar, Ö., Patton, B., & White, A. (2015). Prospective secondary science teachers' argumentation skills and the interaction of these skills with their conceptual knowledge. *Australian Journal of Teacher Education, 40*(9), 132-156.

Acara, D., Tertemizb, N., & Taşdemirc, A. (2018). The effects of STEM training on the academic achievement of 4th graders in science and mathematics and their views on STEM training teachers. *International Electronic Journal of Elementary Education, 10*(4), 505-513.

Adesulu, D. (2016). Breaking news: WAEC releases results, says 53% passed. *Vanguard August 6*. Retrieved from http://www.vanguardngr.com/2016/08/waec-releases-res/

Adeyemi, B. A. (2012). Effects of Computer Assisted Instruction (CAI) on students' achievement in social studies in Osun state, Nigeria. *Mediterranean Journal of Social Sciences, 3*(2), 269-277.

Agboghoroma, T. E., & Oyovwi, E. O. (2015). Evaluating effect of students' academic achievement on identified difficult concepts in senior secondary school biology in Delta State. *Journal of Education and Practice, 6*(30), 117-125.

Aibuedefe, A. F., & Tina, A. E. (2017). *Current challenges in science and technology education in Nigeria.* Paper presented at the 7th World Engineering Education Forum (WEEF), Univseriti Technologi Petronas Kuala Lumpur, Malaysia.

Aidelunuoghene, O. S. (2014). Asuu industrial actions: between ASUU and government is it an issue of rightness? *Journal of Education and Practice, 5*(6), 7-17.

Aiyedun, J. O. (1995). Influence of academic ability of students on achievement in secondary school mathematics. *Ilorin Journal of Education, 15*, 93-102.

Akintunde, A. V. (2018). Towards a socratic method of teaching in the Nigerian classrooms. *Current Educational Research, 1*(5), 58-67.

Akyol, G., Sungur, S., & Tekkaya, C. (2010). The contribution of cognitive and metacognitive strategy use to students' science achievement. *Educational Research and Evaluation, 16*(1), 1-21.

Alghamdi, A. K. H. (2017). The effects of an integrated curriculum on student achievement in Saudi Arabia. *EURASIA Journal of Mathematics Science and Technology Education, 13*(9), 6079-6100.

Allen, R. D., & Moll, M. B. (1986). A realistic approach to teaching Mendelian genetics. *The American Biology Teacher, 48*(4), 227-230.

Alrubai, F. M. R. H. (2014). *The effectiveness of the brainstorming technique towards enhancing creative and critical thinking skills among secondary Iraqi physics students.* (Unpublished PhD thesis ), the University of Malaya, Kuala Lumpur, Malaysia,

Amponsah, K. D., Kotoka, J. K., Beccles, C., & Dlamini, S. N. (2018). Effectiveness of collaboration on low and high achieving school students' comprehension of electrochemistry in South Africa. *European Journal of STEM Education, 3*(2).

Anugwo, M. N. (2015). *Assessment of problems and remediation of science, technology, engineering and mathematics education.* Paper presented at the 9th International Technology, Education and Development Conference (INTED), Madrid, Spain.

Apedoe, X. S., & Schunn, C. D. (2012). Strategies for success: uncovering what makes students successful in design and learning. *Instructional Science, 41*(4), 773-791.

Asghar, A., Ellington, R., Rice, E., Johnson, F., & Prime, G. M. (2012). Supporting STEM education in secondary science contexts. *Interdisciplinary Journal of Problem-Based Learning, 6*(2), 85-125.

Asyari, M., Al Muhdhar, M. H. I., Susilo, H., & Ibrohim. (2016). Improving critical thinking skills through the integration of problem based learning and group investigation. *International Journal for Lesson and Learning Studies, 5*(1), 36-44.

Atabaki, A. M. S., Keshtiaray, N., & Yarmohammadian, M. H. (2015). Scrutiny of critical thinking concept. *International Education Studies, 8*(3), 93-102.

Ateş, Ö., & Eryilmaz, A. (2011). Effectiveness of hands-on and minds-on activities on students' achievement and attitudes towards physics. *Asia-Pacific Forum on Science Learning and Teaching, 12*(1), 1-22.

Atilla, C. (2012). What makes biology learning difficult and effective: Students' views *Educational Research and Reviews, 7*(3), 61-71.

Audu, T. A. (2018). Effects of process-oriented instructional strategies on spatial abilities and basic science achievement of 9th grade students in Kogi State, Nigeria. *Current Journal of Applied Science and Technology, 31*(5), 1-8.

Avargil, S., Herscovitz, O., & Dori, Y. J. (2012). Teaching thinking skills in context-based learning: Teachers' challenges and assessment knowledge. *Journal of Science Education and Technology, 21*(2), 207-225.

Awang-Kanak, F., Masnoddin, M., Matawali, A., Daud, M. A., & Jumat, N. R. (2016). Difficulties experience by science foundation students on basic mendelian genetics topic: A preliminary study. *Transactions on Science and Technology, 3*(1-2), 283-290.

Aydin-Gunbatar, S., Tarkin-Celikkiran, A., Kutucu, E. S., & Ekiz-Kiran, B. (2018). The influence of a design-based elective STEM course on pre-service chemistry teachers' content knowledge, STEM conceptions, and engineering views. *Chemistry Education Research and Practice, 19*(3), 954-972.

Azizah, N., & Putra, A. P. (2015). *Developing biology learning tool in senior high school by using problem solving method to students' learning outcome and their critical thinking skill*. Seminar Nasional XII Pendidikan Biologi FKIP UNS 2015

Bächtold, M. (2013). What do students "construct" according to constructivism in science education? *Research in Science Education, 43*(6), 2477-2496.

Banks, F., & Barlex, D. (2014). Teaching STEM in the secondary school: Helping teachers meet the challenge. *Design and Technology Education: An International Journal, 20*(1), 68-71.

Barak, M., & Dori, Y. J. (2009). Enhancing higher order thinking skills among inservice science teachers via embedded assessment. *Journal of Science Teacher Education, 20*(5), 459-474.

Basham, J. D., & Marino, M. T. (2013). Understanding STEM education and supporting students through universal design for learning. *Teaching Exceptional Children, 45*(4), 8-15.

Basuki, D. K., Besari, A. R. A., Agata, D., & Hasyim, N. S. (2018). Design and implementation of STEM learning module to enhance education learning outcome for middle school. *Advanced Science Letters, 24*(1), 307-309.

Batdı, V. (2014). The effects of a problem-based learning approach on students' attitude levels: A meta-analysis. *Educational Research and Reviews, 9*(9), 272-276.

Beane, J. A. (1995). Curriculum integration and the disciplines of knowledge. *Phi Delta Kappan, 76*(8), 616-622.

Beane, J. A. (2009). Social issues in the middle school curriculum. In S. Totten & J. E. Pedersen (Eds.), *Social issues and service at the middle level*. Charlotte (NC): Information Age Publishing Inc.

Becker, K. H., & Park, K. (2011). Integrative approaches among Science, Technology, Engineering, and Mathematics (STEM) subjects on students' learning: A meta-analysis. *Journal of STEM Education: Innovations and Research,, 12*(5-6), 23-37.

Behar-Horenstien, L. S., & Niu, L. (2011). Teach critical thinking skills in higher education: A review of the literature *Journal of College Teaching & Learning, 8*(2), 25-41.

Bensley, D. A., & Spero, R. A. (2014). Improving critical thinking skills and metacognitive monitoring through direct infusion. *Thinking Skills & Creativity, 12*, 55-68.

Berland, L., Steingut, R., & Ko, P. (2014). High school student perceptions of the utility of the engineering design process: Creating opportunities to engage in engineering practices and apply math and science content. *Journal of Science Education and Technology, 23*(6), 705-720.

Bernard, R. M., Zhang, D., Abrami, P. C., Sicoly, F., Borokhovski, E., & Surkes, M. A. (2008). Exploring the structure of the Watson–Glaser Critical Thinking Appraisal: One scale or many subscales? *Thinking Skills and Creativity, 3*(1), 15-22.

Bernik, M., & Žnidaršič, J. (2012). Solving complex problems with help of experiential learning. *Organizacija, 45*(3), 117-124.

Bevins, S. P., Carter, K., Jones, V. R., Moye, J. J., & Ritz, J. M. (2012). The technology and engineering educator's role in producing a 21st century workforce. *Technology and Engineering Teacher, 72*(3), 8–12.

Billiar, K., Hubelbank, J., Oliva, T., & Camesano, T. (2014). Teaching STEM by design. *Advances in Engineering Education, 4*(1), 1-20.

Black, B. (2012). An overview of a programme of research to support the assessment of critical thinking. *Thinking Skills and Creativity, 7*(2), 122-133.

Blackley, S., & Howell, J. (2015). A STEM narrative: 15 years in the making. *Australian Journal of Teacher Education, 40*(7), 102-112.

Blaik-Hourani, R. (2011). Constructivism and revitalizing social studies. *History Teacher, 44*(2), 227-249.

Bloom, B. (1956). *A taxonomy of educational objectives. Handbook 1: Cognitive domain*. New York: McKay.

Boden, M. A. (2010). Against constructivism. *Constructivist Foundations, 6*(1), 84-89.

Bodzin, A., & Shive, L. (2004). Designing for watershed inquiry. *Applied environmental education and communication, 3*, 249-258.

Boyatzis, R. E. (1998). *Transforming quality information: Thematic analysis and code development*. Thousands Oaks CA: Sage.

Boyer, W., & Crippen, C. L. (2014). Learning and teaching in the 21st century: An education plan for the new millennium developed in British Columbia, Canada. *Childhood Education, 90*(5), 343-353.

Brady, M. (2012). JoLLE forum: The testing juggernaut. *Journal of Language & Literacy Education–University of Georgia, 8*(2), 1-6.

Breiner, J. M., Harkness, S. S., Johnson, C. C., & Koehler, C. M. (2012). What is STEM? A discussion about conceptions of STEM in education and partnerships. *School Science and Mathematics, 112*(1), 3-11.

Brinson, J. R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Computers & Education, 87*, 218-237.

Brookhart, S. M. (2010). *How to assess higher-order thinking skills in your classroom*. Alexandria, VA: Association for Supervision and Curriculum Development.

Brown, R., Brown, J., Reardon, K., & Merrill, C. (2011). Understanding STEM: Current perceptions. *Technology and Engineering Teacher, 70*(6), 5-9.

Burnard, P., Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Analysing and presenting qualitative data. *British dental journal, 204*(8), 429-432.

Bybee, R. W. (2010). Advancing STEM education: A 2020 vision. *Technology and Engineering Teacher, 70*(1), 30-35.

Bybee, R. W. (2013). The next generation science standards and the life sciences. *Science & Children, 50*(6), 7-14.

Capobianco, B. M., Yu, J. H., & French, B. F. (2014). Effects of engineering design-based science on elementary school science students' engineering identity development across gender and grade. *Research in Science Education, 45*(2), 275–292.

Capraro, R. M., Capraro, M. M., & Morgan, J. R. (2013). *STEM project-based learning* (2 ed.). Rotterdam, Netherlands: Sense Publisher.

Capraro, R. M., & Slough, S. W. (2013). Why PBL? Why STEM? Why now? an introduction to STEM project-based learning. In R. M. Capraro, M. M. Capraro, & J. R. Morgan (Eds.), *STEM project-based learning: An integrated Science, Technology, Engineering, and Mathematics (STEM) approach*. Rotterdam, Netherlands: Sense.

Carr, R. L., & Strobel, J. (2011). Integrating engineering into secondary math and science curricula: A course for preparing teachers. 7B-1-7B-4.

Carrio, M., Larramona, P., Banos, J. E., & Perex, J. (2011). The effectiveness of hybrid problem-based learning approach in the teaching of biology: a comparison with lecture-based learning. *Journal of Biological Education, 45*(4), 229-235.

Carvalho, C., Fíuza, E., Conboy, J., Fonseca, J., Santos, J., Gama, A. P., & Salema, M. H. (2015). Critical thinking, real-life problems and feedback in the sciences classroom. *Journal of Turkish Science Education, 12*(2), 21-31.

Casner-Lotto, J., & Barrington, L. (2006). Are they really ready to work; employers perspectives on the basic knowledge and applied skills of new entrants to the 21st Century U.S. workforce. The Conference Board. Retrieved February 25, 2010, from http://www.conference-board.org/Publications/describe.cfm?id=1218.

Chan, Z. C. Y. (2013). Exploring creativity and critical thinking in traditional and innovative problem-based learning groups. *Journal of Clinical Nursing, 22*(15-16), 2298-2307.

Change the Equation. (2012). A business leader's guide to mobilizing state action on STEM. Retrieved from http://changetheequation.org/stem-policy-advocacy.

Chatila, H., & Husseiny, F. A. (2017). Effect of cooperative learning strategy on students' acquisition and practice of scientific skills in biology. *Journal of Education in Science, Environment and Health (JESEH), 3*(1), 88-99.

Chen, S., Huang, C., & Chou, T. (2016). The effect of metacognitive scaffolds on low achievers' laboratory learning. *International Journal of Science and Mathematics Education, 14*(2), 281–296.

Cheng, R. W., Lam, S. F., & Chan, J. C. (2008). When high achievers and low achievers work in the same group: the roles of group heterogeneity and processes in project-based learning. *Br J Educ Psychol, 78*(Pt 2), 205-221.

Cheng, S.-C., She, H.-C., & Huang, L.-Y. (2018). The impact of problem-solving instruction on middle school students' physical science learning: Interplays of knowledge, reasoning, and problem-solving. *EURASIA Journal of Mathematics, Science and Technology Education, 14*(3), 731-743.

Cheng, V. M. (2011). Infusing creativity into Eastern classrooms: Evaluations from student perspectives. *Thinking Skills and Creativity, 6*(1), 67-87.

Choo, S. S., Rotgans, J. I., Yew, E. H., & Schmidt, H. G. (2011). Effect of worksheet scaffolds on student learning in problem-based learning. *Advances in health sciences education, 16(4), 517-528, 16*(4), 517-528.

Chu, Y.-C., & Reid, N. (2012). Genetics at school level: addressing the difficulties. *Research in Science & Technological Education, 30*(3), 285-309.

Chukwuyenum, A. N. (2013). Impact of critical thinking on performance in mathematics among senior secondary school students in Lagos state *Journal of Research & Method in Education (IOSR-JRME), 3*(5), 18-25.

Cohan, A., & Honigsfeld, A. (2011). *Breaking the mold of pre-service and in-service teacher education: Innovative and successful practices for the 21st century*. Plymouth, UK: Rowman and Littlefield Publishers, Inc.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Erlbaum.

Colletti, N. E. (2011). *The impact of completing authentic tasks on the development of critical thinking skills.* (PhD Doctoral dissertation), Capella University, Retrieved from ProQuest Dissertations and Theses database (UMI Number: 3478083)

Corbin, J., & Strauss, A. (2008). *Basics of qualitative research: Techniques and procedures for developing grounded theory*. Los Angeles, California: Sage Publications.

Corley, M. A., & Rauscher, W. C. (2013). Deeper learning through questioning. *The Teaching Excellence in Adult Literacy (TEAL) Center, 12*, 1-5.

Corlu, M. S., Capraro, R. M., & Capraro, M. M. (2014). Introducing STEM education: Implications for educating our teachers in the age of innovation. *Education and Science, 39*(171), 74-85.

Council of Ministers of Education. (1997). *Common taxonomy of science learning outcomes K to 12*. Ottawa, ON, Canada: Author.

Coutinho, S., Wiemer-Hastings, K., Skowronski, J. J., & Britt, M. A. (2005). Metacognition, need for cognition and use of explanations during ongoing learning and problem solving. *Learningand individual differences, 15*, 321-331.

Cox, C., Reynolds, B., Schuchardt, A., & Schunn, C. (2016a). How do secondary level biology teachers make sense of using mathematics in design-based lessons about a biological process? In L. Annetta & J. Minogue (Eds.), *Connecting science and engineering education practices in meaningful ways: Building bridges. Contemporary trends and issues in science education*. Newyork: Springer.

Cox, C., Reynolds, B., Schunn, C., & Schuchardt, A. (2016b). Using mathematics and engineering to solve problems in secondary level biology. *Journal of STEM Education, 17*(1), 22-30.

Crenshaw, P., Hale, E., & Harper, S. L. (2011). Producing intellectual labor in the classroom: The utilization of a critical thinking model to help students take command of their thinking. *Journal of College Teaching & Learning, 8*(7), 13-26.

Cresswell, J. C. (2012). *Educational research planning, conducting, and evaluating quantitative and qualitative research*. Boston MA: Pearson Education Inc.

Creswell, J. W. (2009). *Research design: Qualitative, quantitative, and mixed method approaches*. California: SAGE Publications Inc.

Creswell, J. W. (2014). *Research design qualitative, quantitative and mixed method* (4 ed.). Thousands Oaks: California: SAGE.

Creswell, J. W., & Clark, V. L. P. (2011). *Designing and Conducting Mixed Methods Research*. Thousand Oaks, California: Sage Publications.

Crippen, K. J., & Archambault, L. (2012). Scaffolded inquiry-based instruction with technology: A signature pedagogy for STEM education. *Computers in the Schools, 29*(1-2), 157-173.

Crotty, E. A., Guzey, S. S., Roehrig, G. H., Glancy, A. W., Ring-Whalen, E. A., & Moore, T. J. (2017). Approaches to integrating engineering in STEM units and student achievement gains. *Journal of Pre-College Engineering Education Research (J-PEER), 7*(2), 1-14.

Cruse, A. R. (2012). *Using hands-on learning activities in high school math classes to impact student success.* (doctoral study), Walden University, USA, ProQuest LLC.

Czerniak, C. M., & Johnson, C. C. (2014). Interdisciplinary science and STEM teaching In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education* (2 ed., pp. 395–412). Mahwah, NJ: Lawrence Erlbaum Associates.

Dailey, D. (2017). Using engineering design challenges to engage elementary students with gifts and talents across multiple content areas. *Gifted Child Today, 40*(3), 137-143.

Damilola, O., Adebimbo, A., & Alaba, S. O. (2016). Enhancing students performance in basic science and technology in Nigeria using moodle LMS. *International Scholarly and Scientific Research & Innovation, 10*(5), 1601-1604.

Danmole, B. T., & Lameed, S. N. (2014). Exploring annotated drawing for improving Nigerian secondary school students achievement in genetics *International Journal of Biology Education, 3*(1), 1-11.

Darcy, M., & Henderson, C. (2010). Pedagogical practices and instructional change of physics faculty. *American Journal of Physics, 78(10), 1056–1063, 78*(10), 1058-1063.

Dare, E. A., Ellis, J. A., & Roehrig, G. H. (2018). Understanding science teachers' implementations of integrated STEM curricular units through a phenomenological multiple case study. *International Journal of STEM Education, 5*(1), 1-19.

Dass, P. M. (2015). Teaching STEM effectively with the learning cycle approach. *K-12 STEM Education, 1*(1), 5-12.

Daugherty, M. K. (2010). The 'T' and 'E' in STEM. In ITEEA (Ed.), *The overlooked STEM imperatives: Technology and engineering* (pp. 18-25). Reston, VA: ITEEA.

Davies, M. (2013). Critical thinking and the disciplines reconsidered. *Higher Education Research & Development, 32*(4), 529-544.

Deakin. (2014). Critical Thinking. Deakin University Retrieved from http://www.deakin.edu.au/__data/assets/pdf_file/0012/51222/critical-thinking.pdf

DeJarnette , N. K. (2012). America's children: Providing early exposure to STEM (science, technology, engineering, and math) initiatives. . *Education, 133*(1), 77-85.

Demiral, U. (2018). Examination of critical thinking skills of preservice science teachers: A perspective of social constructivist theory. *Journal of Education and Learning, 7*(4), 179-190.

Dennis, J., & O'Hair, M. J. (2010). Overcoming obstacles in using Authentic Instruction: a comparative case study of high school math & science teachers. *Am Secondary Educ, 38*(2), 4-22.

Denzin, N. K. (1989). *The research act: theoretical introduction to sociological methods*. Englewood Cliffs.NJ: Prentice Hall: Mc Graw-Hill.

Dewey, J. (1902). *The child and the curriculum*. Chicago: University of Chicago Press.

Dick, W., Carey, L., & Carey, J. (2001). *The systemic design of instruction* (5th ed.). Boston: Allyn and Bacon.

Dick, W., Carey, L., & Carey, J. O. (2005). *The systematic design of instruction* (6 ed.). Glenview, IL: Harper Collins.

Dike, V. E. (2009). Technical and vocational education: Key to Nigeria's development, http://www.nigeriavillagesquare.com/articles/victor-dike/technical-and-vocational-educationkey-to-nigerias-development.html.

Dikmenli, M. (2010). Misconceptions of cell division held by student teachers in biology: A drawing analysis *Scientific Research and Essay, 5*(2), 235-247.

Dogru-Atay, P., & Tekkaya, C. (2008). Promoting Students' Learning in Genetics With the Learning Cycle. *The Journal of Experimental Education, 76*(3), 259–280.

Dolan, E., & Grady, J. (2010). Recognizing students' scientific reasoning: A tool for categorizing complexity of reasoning during teaching by inquiry. *J Sci Teacher Educ, 21*(1), 31-55.

Douglas, E. P., Koro-Ljungberg, M., McNeill, N. J., Malcolm, Z. T., & Therriault, D. J. (2012). Moving beyond formulas and fixations: solving open-ended engineering problems. *European Journal of Engineering Education, 37*(6), 627-651.

Drummond, C. K. (2012). Team-based learning to enhance critical thinking skills in entrepreneurship education. *Journal of Entrepreneurship Education, 15*, 57-63.

Dugger, W. (2010). *Evolution of STEM in the United States*. Paper presented at the 6th Biennial International Conference on Technology Education Research, Gold Coast, Queensland.

Duncan, R. G., & Reiser, I. B. (2007). Reasoning across ontologically distinct levels: students' understandings of molecular genetics. *Journal of research in science teaching, 44*(7), 938–959.

Duncan, R. G., & Tseng, K. A. (2010). Designing project-based instruction to foster generative and mechanistic understandings in genetics. *Science Education, 95*(1), 21-56.

Duran, M., & Dökme, I. (2016). The effect of the inquiry-based learning approach on student's critical-thinking skills. *EURASIA Journal of Mathematics, Science and Technology Education, 12*(12), 2887-2908.

Duran, M., & Sendag, S. (2012). A preliminary investigation into critical thinking skills of urban high school students: Role of an IT/STEM program. *Creative Education, 03*(02), 241-250.

Duron, R., Limback, B., & Waugh, W. (2006). Critical thinking framework for any discipline. *International Journal of Teaching and Learning in Higher Education, 17*(2), 160-166.

Dwyer, C. P., Hogan, M. J., & Stewart, I. (2014). An integrated critical thinking framework for the 21st century. *Thinking Skills and Creativity, 12*, 43-52.

Edwards, S. (2014). *Getting them to talk: A guide to leading discussions in middle grades classrooms*. Westerville, OH: Association for Middle Level Education.

Elson, S. B., Hartman, R., Beatty, A., Trippe, M., & Buckley, K. (2018). Critical analytic thinking skills: Do they predict job-related task performance above and beyond general intelligence? *Personnel Assessment and Decisions, 4*(1), 9-29.

English, L. D. (2016). STEM education K-12: Perspectives on integration. *International Journal of STEM Education, 3*(3), 1-8.

English, L. D., Hudson, P., & Dawes, L. A. (2013). Engineering-based problem solving in the middle school: design and construction with simple machines. *Journal of Pre-College Engineering Education Research (J-PEER), 3*(2), 1-13.

English, L. D., & King, D. (2018). STEM integration in sixth grade: Designing and constructing paper bridges. *International Journal of Science and Mathematics Education*(Online advance copy).

English, L. D., King, D., & Smeed, J. (2016). Advancing integrated STEM learning through engineering design: Sixth-grade students' design and construction of earthquake resistant buildings. *The Journal of Educational Research, 110*(3), 255-271.

English, L. D., & King, D. T. (2015). STEM learning through engineering design: fourth-grade students' investigations in aerospace. *International Journal of STEM Education, 2*(1), 1-18.

Ennis, R. (1991). Critical thinking: A streamlined conception. *Teaching Philosophy, 14*, 15-24.

Ennis, R. H. (1984). Problems in testing informal logic critical thinking reasoning ability. *Informal Logic, 6*, 3-9.

Ennis, R. H., & Millman, J. (1985). *Cornell critical thinking test*. Pacific Grove, CA: Critical Thinking Books & Software.

Ennis, R. H., & Wier, E. (1985). *The Ennis-Wier critical thinking essay test*. Pacific Grove, CA: Midwest publications.

Erinosho, S. Y. (2013). How do students perceive the difficulty of physics in secondary school? An exploratory study in Nigeria. *International Journal for Cross-disciplinary Subjects in Education, 3*(3), 1510-1515.

Erkens, C., Schimmer, T., & Vagle, N. (2019). *Growing tomorrow's citizens in today's classrooms: Assessing seven critical competencies*. Bloomington, IN: Solution Tree.

Estes, T. H., Gunter, M. A., & Mintz, S. L. (2010). *Instruction: A models approach* (6 ed.). Boston, MA: Pearson.

Etim, J. (2005). Curriculum integration: The why and how. In J. Etim (Ed.), *Curriculum integration K-12 theory and practice*. Lanham, MD: University Press of America.

Evren, A., Bati, K., & Yilmaz, S. (2012). The effect of using v-dia- grams in science and technology laboratory teaching on preservice teachers' critical thinking disposition *Procedia Social and Behav-ioral Sciences, 46*, 2267-2272.

Ezenwa, V. I. (2005). Concept mapping: A veritable tool in science education. The seventh inaugural lecture series of the Federal University of Technology Minna.

Ezeudu, F. O., Ofoegbu, T. O., & Anyaegbunnam, N. J. (2013). Restructuring STM (Science, Technology, and Mathematics) education for entrepreneurship. *US-China Education Review A, 3*(1), 27-32.

Facione, P. A. (1990). *Critical thinking: A statement of expert consen-sus for purposes of educational assessment and instruction*. Millbrae, California,: California Academic Press.

Facione, P. A. (2006). Critical thinking: What it is and why it counts. Retrieved July 17, 2014, from www.insightassessment.com.

Facione, P. A. (2007). *Critical thinking: What it is and why it counts*. Millbrae, CA: California Academic Press.

Facione, P. A. (2011). *Measured reasons and critical thinking*. Millbrae, CA: The California Academic Press.

Facione, P. A., Facione, N. C., & Giancarlo, C. A. F. (1996). *The California Critical Thinking Disposition Inventory*. Millbrae: California Academic Press.

Fahim, M., & Masouleh, N. (2012). Critical thinking in higher education: A pedagogical look *Theory & Practice in Language Studies, 2*(7), 1370-1375.

Fantz, T., & Grant, M. (2013). An engineering design STEM project: T-shirt launcher. *Technology and Engineering Teacher, 72*(8), 14-20.

Federal Republic of Nigeria. (2004, P32). *National policy on education*. Lagos: Federal Government Press.

FitzPatrick, B., & Schulz, H. (2015). Do curriculum outcomes and assessment activities in science encourage higher order thinking? *Canadian Journal of Science, Mathematics and Technology Education, 15*(2), 136-154.

Foong, C.-C., & Daniel, E. G. S. (2013). Students' argumentation skills across two socio-scientific issues in a confucian classroom: Is transfer possible? *International Journal of Science Education, 35*(14), 2331-2355.

Forawi, S. A. (2016). Standard-based science education and critical thinking. *Thinking Skills and Creativity, 20*, 52-62.

Fortus, D., Krajcik, J., Dershimer, R. C., Marx, R. W., & Mamlok-Naaman, R. (2005). Design-based science and real-world problem-solving. *International Journal of Science Education, 27*(7), 855-879.

Fraenkel, J., & Wallen, N. (2007). *How to design and evaluate research in education* (6 ed.). New York: McGraw-Hill.

Freidenreich, H. B., Duncan, R. G., & Shea, N. (2011). Exploring middle school students' understanding of three conceptual models in genetics. *International Journal of Science Education, 33*(17), 2323-2349.

Frykholm , J., & Glasson , G. (2005). Connecting science and mathematics instruction: pedagogical context knowledge for teachers. *Sch Sci Math, 105*(3), 127-141.

Furner, J., & Kumar, D. (2007). The mathematics and science integration argument: a stand for teacher education. *Eurasia J Math Sci Technol Educ, 3*(3), 185–189.

Gajjar, N. B. (2013). Ethical consideration in research. *International Journal for Research in Education, 2*(7), 8-15.

Gallant, D. (2010). *Science, technology, engineering, and mathematics (STEM) education.* . Columbus, OH: The McGraw-Hill Companies.

Gallant, D. J. (2011). Science, technology, engineering, and mathematics (STEM) education. Retrieved from https://www.mheonline.com/mhmymath/wp-content/themes/souffle/_PDFS/stem_education.pdf

Galloway, K., & Anderson, N. (2014). Cootie genetics: Simulating model's experiments to understand the laws of inheritance. *The American Biology Teacher, 76*(3), 189-193.

Gambari, A. I. (2010). *Effectiveness of computer-assisted instructional package in cooperative settings on senior secondary school students' performance in physics, in Minna.* (PhD Dessertation), University of Illorin, Nigeria,

Gambari, A. I., James, M., & Olumorin, C. C. (2013a). Effectiveness of video-based cooperative learning strategy on high, medium and low academic achievers. *The African Symposium: An online journal of the African Educational Research Network, 13*(2), 77-85.

Gambari, A. I., Yaki, A. A., Gana, E. S., & Ughovwa, Q. E. (2013b). Improving secondary school students' achievement and retention in biology through video-based multimedia instruction. *InSight: A Journal of Scholarly Teaching, 9*, 78-91.

Garrison, W. M. (2004). Profiles of classroom practices in US public schools. *School Effectiveness School Improvement, 15*, 377-406.

Ge, X., Planas, L. G., & Er, N. (2010). A cognitive support system to scaffold students' problem-based learning in a web-based environment. *The Interdisciplinary Journal of Problem-Based Learning, 4*(1), 30-56.

Germaine, R., Richards, J., Koeller, M., & Schubert-Irastorza, C. (2016). Purposeful use of 21st century skills in higher education. *Journal of Research in Innovative Teaching, 9*(1), 19-29.

Ghanizadeh, A. (2016). The interplay between reflective thinking, critical thinking, self-monitoring, and academic achievement in higher education. *Higher Education, 74*(244), 1-14.

Gimba, R. W., Hassan, A. M., Yaki, A. A., & Chado, A. M. (2018). Teachers' and students' perceptions on the problems of effective teaching and learning of science and technology in Junior Secondary Schools. *Malaysian Online Journal of Educational Sciences, 6*(1), 34-42.

Gok, T. (2012). The impact of peer instruction on college students' beliefs about physics and conceptual understanding of electricity and magnetism. *International Journal of Science and Mathematics Education, 10*, 417-436.

Gonen, S., & Kocakaya, S. (2010). A physics lesson designed according to 7E model with the help of instructional technology (lesson plan). *Turkish Online Journal of Distance Education-TOJDE, 11*(1), 98-113.

Gonzalez, H. B., & Kuenzi, J. (2012). Congressional research service Science, Technology, Engineering, and Mathematics (STEM) education: A primer.

Retrieved from http://www.stemedcoalition.org/wp-content/uploads/2010/05/STEM-Education-Primer.pdf.

Goovaerts, L., De Cock, M., Struyven, K., & Dehaene, W. (2018). Developing a module to teach thermodynamics in an integrated way to 16 year old pupils. *European Journal of STEM Education, Online Advance Copy* 1-11.

Grumbine, R. A. (2006). Using manipulatives to teach basic Mendelian genetics concepts. *The American Biology Teacher, 68*(8), 117-123.

Guzey, S. S., Harwell, M., Moreno, M., Peralta, Y., & Moore, T. J. (2017a). The impact of design-based STEM integration curricula on student achievement in engineering, science, and mathematics. *Journal of Science Education and Technology, 26*(2), 207-222.

Guzey, S. S., Moore, T. J., & Morse, G. (2016). Student interest in engineering design-based science. *School Science and Mathematics, 116*(8), 411-419.

Guzey, S. S., Ring-Whalen, E. A., Harwell, M., & Peralta, Y. (2017b). Life STEM: A case study of life science learning through engineering design. *International Journal of Science and Mathematics Education*(Advance online publication).

Haambokoma, C. (2007). Nature and Causes of Learning Difficulties in Genetics at High School Level in Zambia. *Journal of International Development and Cooperation, 13*(1), 1-9.

Halpern , D. F. (1998). Teaching critical thinking for transfer across domains: Disposition, skills, structure training, and metacognitive monitoring. *American Psychologist, 53(4), 449., 53*(4), 449-455.

Halpern, D. F. (2010). *The halpern critical thinking assessment manual*. Austria: Schuhfried.

Halpern, D. F. (2014). *Thought and knowledge: An introduction to critical thinking*. New York, NY: Psychology Press.

Hammersley, M. (1993). On the teacher as researcher. *Educational Action Research, 1*(3), 425-445.

Hammersley, M. (2015). On ethical principles for social research. *International Journal of Social Research Methodology, 18*, 433–449.

Han, H. S., & Brown, E. T. (2013). Effects of critical thinking intervention for early childhood teacher candidates. *The Teacher Educator, 48*(2), 110-127.

Han, S., Capraro, R., & Capraro, M. M. (2014). How Science, Technology, Engineering and Mathematics (STEM) project-based learning affects high, middle, and low achievers differently: The impact of student factors on achievement. *International Journal of Science and Mathematics Education, 13*(5), 1089-1113.

Han , S., Capraro, R., & Capraro, M. M. (2015). How science, technology, engineering and mathematics (STEM) project-based learning affects high, middle, and low achievers differently: the impact of student factors on achievement. *International Journal of Science and Mathematics Education, 13*, 1089-1113.

Han, S., Rosli, R., Capraro, M. M., & Capraro, R. M. (2016). The effect of Science, Technology, Engineering and Mathematics (STEM) Project Based Learning (PBL) on students' achievement in four mathematics topics. *Journal of Turkish Science Education, 13*(Special Issue), 3-29.

Hansen, M., & Gonzalez, T. (2014). Investigating the relationship between STEM learning principles and student achievement in math and science. *American Journal of Education, 120*(2), 139-171.

Hanushek, E. A., & Wößmann, L. (2008). Education and economic growth. In P. Peterson, E. Baker and B. McGaw (Eds.), International Encyclopedia of Education (3rd ed.), (pp. 245-252). Retrieved from http://edpro.stanford.edu/hanushek/admin/pages/files/uploads/hanushek_woessmann%20%2020010%20international%20encyclopedia.pdf.

Hashim, Y. (1999). Are instructional design elements being used in module writing? *British Journal of Educational Technology, 30*(4), 341–358.

Hatcher, D. L., & Spencer, L. A. (2005). *Reasoning and Writting: From critical thinking to Composition.* (3 ed.). Boston: American Press.

Hattie, J. A. C. (2012). *Visible learning for teachers. Maximizing impact on achievement*. Oxford, UK: Routledge.

Heit, E., & Rotello, C. M. (2010). Relations between inductive reasoning and deductive reasoning. *J Exp Psychol Learn Mem Cogn, 36*(3), 805-812.

Herschbach, D. R. (2011). The STEM initiative: constraints and challenges. *Journal of STEM Teacher Education, 48*(1), 96-121.

Hiong, L. C., & Kamisah, O. (2015). An interdisciplinary approach for Biology, Technology, Engineering and Mathematics (BTEM) to enhance 21st century skills in Malaysia. *K-12 STEM Education, 1*(3), 137-147.

Hirca, N. D. (2011). Impact of problem-based learning to students and teachers. *Asia-Pacific forum on science learning & teaching, 12*(1), 1-19.

Hmelo-Silver, C. E. (2004). Problem-based learning: what and how students learn. *Educational Psychology Review, 16*(3), 235-266.

Honey, M., Pearson, G., & Schweingruber, A. (2014). *STEM integration in K-12 education: status, prospects, and an agenda for research*. Washington: National Academies Press.

Hornby, G., Witte, C., & Mitcell, D. (2011). Policies and practices of ability grouping in New Zealand intermediate schools. *Support for learning, 26*(3), 92-96.

Howell, D. C. (2007). *Statistical methods for psychology*. Belmont, CA: Thompsom Wardsworth.

Howells, K. (2018). *The future of education and skills: education 2030: the future we want. Working Paper.* Paris: OECD.

Ibrahim, A., Aulls, M. W., & Shore, B. M. (2016). Teachers' roles, students' personalities, inquiry learning outcomes, and practices of science and engineering:The development and validation of the McGill attainment value for inquiry engagement survey in STEM disciplines. *International Journal of Science and Mathematics Education, 15*(7), 1195-1215.

ICASE. (2013). *The Kuching declaration.* Paper presented at the Final proceeding of the World Conference on Science and Technology Education (WorldSTE2013), Kuching, Malaysia.

Jalmo, T., & Suwand, T. (2018). Biology education students' mental models on genetic concepts. *Journal of Baltic Science Education, 17*(3), 474-485.

Jamali, S. M., Zain, A. N. M., Samsudin, M. A., & Ebrahim, N. A. (2017). Self-efficacy, scientific reasoning, and learning achievement in the STEM project-based learning literature. *Journal of Nusantara Studies, 2*(2), 29-43.

James, J. S. (2014). *Science, Technology, Engineering, and Mathematics (STEM) curriculum and seventh grade mathematics and science achievement.* (Ph.D), Grand Canyon University Phoenix, Arizona, (UMI: 3614935)

Jatmiko, B., Prahani, B. K., Munasir, Z. A., Imam Supardi, Wicaksono, I., Erlina, N., . . . Zainuddin. (2018). The Comparison of OR-IPA teaching model and problem based learning model effectiveness to improve critical thinking skills of pre-service physics teachers. *Journal of Baltic Science Education, 17*(2), 300-319.

Jibrin, A. G., & Zayum, S. D. (2012). Effects of Peer Tutoring Instructional Method on the Academic Achievement in Biology among Secondary School Students in Zaria Metropolis, Nigeria. *Journal of Research in Education and Society, 3*(2), 13-17.

Johns, R. A. (2012). What were they thinking. *The Science Teacher, 79*(3), 66-70.

Johnson, B. (2011). STEM education and hands-on program. Retrieved from http://WWW.ahwatukee.com/communityfocus/article-e33d3bb0-80id-11eO-816b-001cc4c03286.html

Johnson, B., & Christensen, L. (2012). *Educational research: Quantitative, qualitative, and mixed approaches*. Thousand Oak, CA: Sage Publishing.

Johnson, T. R. (2016). Violation of the homogeneity of regression slopes assumption in ANCOVA for two-group pre-post designs: Tutorial on a modified Johnson-Neyman procedure. *The Quantitative Methods for Psychology, 12*(3), 253-263.

Jonassen, D. H. (2011). *Learning to solve problems: A handbook for designing problem solving learning environments*. New York, NY: Routledge.

Jones, H., & Twiss, B. C. (1978). *Forecasting technology for planning decisions*. New York: MacMillan.

Jøsang, A. (2008). *Abductive reasoning with uncertainty.* Paper presented at the The 12th International Conference on Information Processing and Management of Uncertainty (IPMU2008), Malaga, Spain.

Juliani, A. J. (2015). *Inquiry and innovation in the classroom: Using 20% time, genius hour, and PBL to drive student success*. New York, NY: Taylor & Francis.

Jungwirth, E., & Dreyfus, A. (1990). Diagnosing the attainment of basic enquiry skills: the 100-year old quest for critical thinking. *Journal of Biological Education, 24*(1), 42-49.

Kajamies, A., Vauras, M., & Kinnunen, R. (2010). Instructing low-achievers in mathematical word problem solving. *Scandinavian Journal of Educational Research, 54*(4), 335-355.

Kalelioğlu, F., & Gülbahar, Y. (2014). The effect of instructional techniques on critical thinking and critical thinking dispositions in online discussion. *Educational Technology & Society, 17*(1), 248-258.

Kanadlı, S. (2019). A Meta-Summary of Qualitative Findings about STEM Education. *International Journal of Instruction, 12*(1), 959-976.

Karademİr, Ç. A., & Uçak, E. (2009). The effect of between class ability grouping on 7th grade students' academic achievement on the unit "if there were no pressure?" in science and technology education. *Eurasian Journal of Physics and Chemistry Education, 1* (1), 32-44.

Karbalaei, A. (2012). Critical thinking and academic achievement. *Medellín – Colombia, 17*(2), 121-128.

Karpudewan, M., & Chong, K. M. (2017). The effects of classroom learning environment and laboratory learning environment on the attitude towards learning science in the 21st-century science lessons. *Malaysian Journal of Learning and Instruction (MJLI), Special issue on Graduate Students Research on Education*, 25-45.

Kasim, N. H., & Ahmad, C. N. C. (2018). PRO-STEM module: The development and validation. *International Journal of Academic Research in Business and Social Sciences, 8*(1), 728-739.

Katehi, L., Pearson, G., & Feder, M. (2009). *National Academy of Engineering and National Research Council Engineering in K-12 education*. Washington, DC: National Academies Press.

Kaymakcı, S. (2012). A review of studies on worksheets in Turkey. *US-China Education Review A, 1*, 57-64.

Kek, M. Y. C. A., & Huijser, H. (2011). The power of problem-based learning in developing critical thinking skills: preparing students for tomorrow's digital futures in today's classrooms. *Higher Education Research & Development, 30*(3), 329-341.

Kennedy, T. J., & Odell, M. R. L. (2014). Engaging students in STEM education. *Science Education International, 25*(3), 246-258.

Kertil, M., & Gurel, C. (2016). Mathematical modelling: A bridge to STEM education. *International Journal of Education in Mathematics, Science and Technology, 4*(1), 44-45.

Khalid, F., Ahmad, M., Karim, A. A., Daud, M. Y., & Din, R. (2015). Reflective thinking: An analysis of students' reflections in their learning about computers in education. *Creative Education, 6*(20), 2160-2168.

Khazaeenezhad, B., Barati, H., & Jafarzade, M. (2012). Ability grouping as a way towards more academic success in teaching EFL - a case of iranian undergraduates. *English Language Teaching, 5*(7), 81-88.

Kim, K., Sharma, P., Land, S. M., & Furlong, K. P. (2013). Effects of active learning on enhancing student critical thinking in an undergraduate general science course. *Innovative Higher Education, 38*, 223-235.

Kim, S. H., & Choi, S.-Y. (2016). Exploring the influences of global learning using web technologies on 21st century skills and global learning attitudes. *Advance Science and technology Letters, 127*, 135-139.

Kivunja, C. (2014). Do you want your students to be job-ready with 21st century skills? Change pedagogies: A pedagogical paradigm shift from Vygotskyian social constructivism to critical thinking, problem solving and siemens' digital connectivism. *International Journal of Higher Education, 3*(3), 81-91.

Kivunja, C. (2015). Exploring the pedagogical meaning and implications of the 4Cs "Super Skills" for the 21st century through Bruner's 5E Lenses of knowledge construction to improve pedagogies of the new learning paradigm. *Creative Education, 6*(2), 224-239.

Klassen, A. C., Creswell, J., Clark, V., Smith, K., & Meissner, M. (2012). Best practices in mixed methods for quality of life research. *Quality of Life Research, 21*(3), 377-380.

Kola, A. J. (2013). Importance of science education to national development and problems militating against its development. *American Journal of Educational Research, 1*(7), 225-229.

Krathwohl, D. R. (2014). A revision of Bloom ' s taxonomy. *Theory Pract, 41*, 37-41.

Kraus, S., Sears, S. R., & Burke, B. L. (2013). Is truthiness enough? Classroom activities for encouraging evidence-based critical thinking. *The Journal of Effective Teaching, 13*(2), 83-93.

Kristanto, A., Mustaji, M., & Mariono, A. (2017). The development of instructional materials E-Learning based on blended learning. *International Education Studies, 10*(7), 10-17.

Kruse, K. (2009). Introduction to instructional design and the ADDIE model. Retrieved 13 Feb, 2017 from Retrieved from http://www.transformativedesigns.com/id_systems.html

Ku, K. Y. L., Ho, I. T., Hau, K.-T., & Lai, E. C. M. (2014). Integrating direct and inquiry-based instruction in the teaching of critical thinking: an intervention study. *Instructional Science, 42*(2), 251-269.

Kuhn, D. (2010). Teaching and learning science as argument. *Science Education, 94*(5), 810-824.

Kulo, V., & Bodzin, A. (2012). The Impact of a Geospatial Technology-Supported Energy Curriculum on Middle School Students' Science Achievement. *Journal of Science Education and Technology, 22*(1), 25-36.

Kuo, Y.-R., Tuan, H.-L., & Chin, C.-C. (2018). Examining low and non-low achievers' motivation towards science learning under inquiry-based instruction. *International Journal of Science and Mathematics Education, Online advance copy*.

Kurfiss, J. G. (1988). *Critical thinking: Theory, research, practice, and possibilities*. Washington, DC: Association for the study of Higher Education.

Kwan, Y. W., & Wong, A. F. L. (2015). Effects of the constructivist learning environment on students' critical thinking ability: Cognitive and motivational variables as mediators. *International Journal of Educational Research, 70*, 68-79.

Laboy-Rush, D. (2011). Integrated STEM education through project-based learning retrieved from www.learning.com/imaginemars 17/12/2014. Retrieved from

Lamanauskas, V., & Augienė, D. (2015). Development of scientific research activity in university: A position of the experts. *Procedia - Social and Behavioral Sciences, 167*, 131-140.

Lammi, M. D., & Denson, C. (2013). *Pre-service teachers' modeling as a way of thinking in engineering design. Paper presented at the 120th American Society for Engineering Education Annual Conference & Exposition, Atlanta, GA. Retrieved from http://www.asee.org/public/conferences/20/papers/5867/download 19/06/2015*.

Langdon, D., McKittrick, G., Beede, D., Khan, B., & Doms, M. (2011). STEM: Good jobs now and for the future, U.S. Department of Commerce Economics and Statistics Administration retrieved from http://www.esa.doc.gov/sites/default/files/stemfinalyjuly14_1.pdf.

Lawson, A. (2004). The nature and development of scientific reasoning: a synthetic view. International. *Journal of Science and Mathematics Education, 2*(3), 307-338.

Lay, A.-N., & Osman, K. (2017). Developing 21st-century skills through a constructivist-constructionist learning environment. *K-12 STEM Education, 3*(2), 205-215.

Lay, A.-N., & Osman, K. (2018). Integrated STEM education: Promoting STEM literacy and 21st-century learning. In M. Shelley & S. A. Kiray (Eds.), *Research highlights in STEM Education* (pp. 66-80). Iowa, USA: ISRES Publishing.

Lazarowitz, R., & Naim, R. (2012). Learning the Cell Structures with Three-Dimensional Models: Students' Achievement by Methods, Type of School and Questions' Cognitive Level. *Journal of Science Education and Technology, 22*(4), 500-508.

Lederman, N. G., & Lederman, J. S. (2013). Is it STEM or "S & M" that we truly love? *Journal of Science Teacher Education, 24*(8), 1237–1240.

Levin-Goldberg, J. (2012). Teaching generation TechX with the 4Cs: Using technology to integrate 21st century skills. *Journal of Instructional Research, 1*, 59–66.

Lewis, J., & Wood-Robinson, C. (2000). Genes, chromosomes, cell division and inheritance - do students see any relationship? *International Journal of Science Education, 22*(2), 177-195.

Li, Q., & Payne, G. (2016). Improving student's critical thinking through technology at historically black institutions. *European Journal of Educational Sciences, EJES, 3*(3), 16-25.

Lin, K.-Y., Hsiao, H.-S., Williams, P. J., & Chen, Y.-H. (2019). Effects of 6E-oriented STEM practical activities in cultivating middle school students' attitudes toward technology and technological inquiry ability. *Research in Science & Technological Education*(Advanced Online Copy), 1-18.

Lin, S., & Lin, H. (2016). Learning nanotechnology with texts and comics: The impacts on students of different achievement levels. *International Journal of Science Education, 38*(8), 1373-1391.

Lin, S. S. (2014). Science and non-science undergraduate students' critical thinking and argumentation performance in reading a science news report. . *International Journal of Science and Mathematics Education, 12*(5), 1023-1046.

Lipman, M. (1988). Critical Thinking — What can it be? Educational. *Leadership, 47*, 38-43.

Liu, M., Wivagg, J., Geurtz, R., Lee, S. T., & Chang, H. M. (2012). Examining how middle school science teachers implement a multimedia-enriched problem-based learning environment. *Interdisciplinary Journal of Problem-based Learning, 6*(2), 46-84.

Liu, O. L., Frankel, L., & Roohr, K. C. (2014). *Assessing critical thinking in higher education: Current state and directions for next-generation assessment* (Research Report No. RR-14-10). Retrieved from Princeton, NJ: https://files.eric.ed.gov/fulltext/EJ1109287.pdf

Loes, C. N., & Pascarella, E. T. (2017). Collaborative learning and critical thinking: testing the link. *The Journal of Higher Education, 1-28.*, 1-28.

Lombard, B. J. J., & Grosser, M. M. (2004). Critical thinking abilities among prospective educators: ideals versus realities. *South African Journal of Education, 24*(3), 212-216.

Lottero-Perdue, P., Roland, C., Turner, K., & Pettitt, J. (2013). Learning about the engineering design process through earth science. *Science Scope, 36(6), 62, 36*(6), 62-72.

Lou, S.-J., Shih, R.-C., Ray Diez, C., & Tseng, K.-H. (2011). The impact of problem-based learning strategies on STEM knowledge integration and attitudes: an exploratory study among female Taiwanese senior high school students. *International Journal of Technology and Design Education, 21*(2), 195-215.

Lynch, S. J., Behrend, T., Burton, E. P., & Means, B. (2013). *Inclusive STEM-focused high schools: STEM education policy and opportunity structures* Paper presented at the annual conference of National Association for Research in Science Teaching (NARST), Rio Grande, Puerto Rico.

Mahoney, M. (2010). Students' attitudes toward STEM: Development of an instrument for high school STEM-based programs. *Journal of Technology Studies, 36*(1), 24-36.

Maloney, J. (2007). Children's roles and use of evidence in science: an analysis of decision-making in small groups. *British Educational Research Journal, 33*(3), 371-401.

Mandusic, D., & Blaskovic, L. (2015). The impact of collaborative learning to critically think. *Trakia Journal of Science, 13*(Suppl.1), 426-428.

Mangold, J., & Robinson, S. (2013). *The engineering design process as a problem solving and learning tool in K-12 classrooms.* Paper presented at the Proceedings of the 2013 American Society for Engineering Education Annual Conference and Exposition, Atlanta, GA.

Mapeala, R., & Siew, N. M. (2015). The development and validation of a test of science critical thinking for fifth graders *SpringerPlus, 4*(741), 1-13.

Marin, L. M., & Halpern, D. F. (2011). Pedagogy for developing critical thinking in adolescents: Explicit instruction produces greatest gains. *Thinking Skills and Creativity, 6*(1), 1-13.

Marshall, C., & Rossman, G. B. (2011). *Designing qualitative research* (5th ed.). Thousand Oaks, CA: Sage.

Martinez, S. L., & Stager, G. (2013). *Invent to learn: Making, tinkering, and engineering in the classroom*. Torrance, CA.: Constructing Modern Knowledge Press.

Mathis, C. A., Siverling, E. A., Moore, T. J., Douglas, K. A., & Guzey, S. S. (2018). Supporting engineering design ideas with science and mathematics: A case study of middle school life science students. *International Journal of Education in Mathematics, Science and Technology (IJEMST), 6*(4), 424-442.

Maxwell, J. A. (2013). *Qualitative research design: An interactive approach* (3rd ed.). Thousand Oaks, CA: Sage.

Mayfield, M. (2011). Creating training and development programs: using the ADDIE method", Development and Learning in Organizations. *An International Journal, 25*(3), 19-22.

McCrae, N. (2011). Nurturing critical thinking and academic freedom in the 21st century university *International Journal of Teaching & Learning in Higher Education, 23*(1), 128-134.

McDonald, G. (2012). Teaching Critical & Analytical Thinking in High School Biology? *The American Biology Teacher, 74*(3), 178-181.

McFadden, J. R., & Roehrig, G. H. (2017). Exploring teacher design team endeavors while creating an elementary-focused STEM-integrated curriculum. *Int J STEM Educ, 4*(21), 1-22.

McPeck, J. (1981). *Critical thinking and education*. Oxford: Martin Robertson.

Mehta, J., & Fine, S. (2019). *In serach of deeper learning: The quest to remake the American high school*. London: Harvard University Press.

Merriam, S. B., & Caffarella, R. S. (1999). *Learning in adulthoo: A comprehensive guide*. San Francisco: Jossey-Bass.

Meyer, X. S., & Crawford, B. A. (2015). Multicultural Inquiry Toward Demystifying Scientific Culture and Learning Science. *Science Education, 99*(4), 617-637.

Meyrick, K. (2011). How STEM education improves student learning. *Meridian K-12 School Computer Technologies Journal, 14*(1), 1-6.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: A sourcebook of new methods*. Thousand Oaks CA: Sage.

Mills Shaw, K. R., Van Horne, K., Zhang, H., & Boughman, J. (2008). Essay contest reveals misconceptions of high school students in genetics content. *Genetics, 178*(3), 1157-1168.

Ministry of Education. (2013). Malaysian education blueprint 2013-2025; Pre-school to post-secondary school.

Monvises, A., Ruenwongsa, P., Panijpan, B., & Sriwattanarothai, N. (2011). Promoting student understanding of genetics and biodiversity by using inquiry-based and hands-on learning unit with an emphasis on guided inquiry. *The International Journal of Learning, 17*(12), 227-240.

Moore, T. J. (2011). Critical thinking and disciplinary thinking: A continuing debate. *Higher Education Research and deveolpment, 30*(3), 261-274.

Moore, T. J., Johnson, C. C., & Peters-Burton, E. E. (2015). The need for a STEM road map. In C. C. Johnson, E. E. Peters-Burton, & T. J. Moore (Eds.), *STEM road map: A framework for integrated STEM education* (pp. 3–12). New York. NY: Routledge.

Moore, T. J., & Smith, K. A. (2014). Advancing the state of the art of STEM integration. *Journal of STEM Education, 15*(1), 5-10.

Morgan, J. A., Porter, J. R., & Zhan, W. (2011). *Krisys: A low-cost, high-impact recruiting and outreach tool.* Paper presented at the 2011 ASEE Annual Conference & Exposition, San Antonio, TX.

Morrison, G. R. (2010). *Designing Effective Instruction* New York, NY: John Wiley & Sons.

Morrison, J., Ross, S. M., & Kemp, J. E. (2004). *Designing effective instruction*. Hoboken, NJ: John Wiley & Sons Inc.

Morrison, J. S. (2006). Attributes of STEM education: The student, the academy, the classroom. Retrieved from http://www.tiesteach.org/documents/ Jans%20pdf%20Attributes_of_STEM_Education-1 .pdf.

Mthethwa-Kunene, E., Onwu, G. O., & de Villiers, R. (2015). Exploring biology teachers' pedagogical content knowledge in the teaching of genetics in Swaziland science classrooms. *International Journal of Science Education, 37*(7), 1140-1165.

Mundy, L. (2005). Gates "appalled" by high schools. The Seattle Times. http://seattletimes.nwsource.com/html/education/2002191433_gates27m.html

Muraya, D. N., & Kimamo, G. (2011). Effects of cooperative learning approach on biology mean achievement scores of secondary school students' in Machakos District, Kenya. *Educational Research and Reviews, 6*(12), 726-745.

Nadelson, L. S., Callahan, J., Pyke, P., Hay, A., Dance, M., & Pfiester, J. (2013). Teacher STEM perception and preparation: Inquiry-based STEM professional development for elementary teachers. *The Journal of Educational Research, 106*(2), 157-168.

Nathan, R. (2010). Back to the future?: The role of critical thinking and high levels of reading comprehension in the 21st century. *California English, 16*(2), 6-9.

National Academy of Engineers, & National Research Council. (2009). *Engineering in K-12 education: understanding the status and improving the prospects*. Washington: National Academies Press, .

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, D.C: The National Academies Press.

National Science Foundation. (2012). NSF at a glance. Washington, DC. Retrieved from http://www.nsf.gov

Ndagi, M. U. (2014). WASSCE Result: Reflection of a failed system. *Daily Trust Newspaper*.

NGSS Lead States. (2013). *Next Generation Science Standards (NGSS): For states, by states*. Washington DC: National Academies Press.

Niemi, D., Baker, E. L., & Sylvester, R. M. (2007). Scaling up, scaling down: Seven years of performance assessment development in the nation's second largest school district *Educational Assessment, 12*(3), 195-214.

Ning, F. (2013). Increasing high school students' interest in STEM Education through collaborative brainstorming with Yo-Yos. *Journal of STEM Education, 14*(4), 8-14.

Nisa, E. K., Jatmiko, B., & Koestiari, T. (2018). Development of guided inquiry-based physics teaching materials to increase critical thinking skills of high school students. *Jurnal Pendidikan Fisika Indonesia, 14*(1), 18-25.

Nisa, E. K., Koestiari, T., Habibbulloh, M., & Jatmiko, B. (2018). Effectiveness of guided inquiry learning model to improve students' critical thinking skills at senior high school. *Journal of Physics: Conference Series, 997*, 1-6.

Nnabugwu, F. (2013, 23rd, May). UNESCO, Nigeria dearth of mathematics, science student teachers. *Vanguard Newspapers May 23rd*.

Ntemngwa, C., & Oliver, J. S. (2018). The implementation of Integrated Science Technology, Engineering and Mathematics (STEM) instruction using robotics in the middle school science classroom. *International Journal of Education in Mathematics, Science and Technology, 6*(1), 12-40.

Nuswowati, M., & Purwanti, E. (2018). The effectiveness of module with critical thinking approach on hydrolysis and buffer materials in chemistry learning. *Journal of Physics: Conference Series, 983*, 1-6.

Obanya, P. (2004). *The dilemma of education in Africa*. Ibadan: Heinemann Educational Books Nigeria Plc.

Odom, A. L., & Bell, C. V. (2011). Distinguishing among declarative, descriptive and causal questions to guide field investigation and student assessment. *Journal of Biological Education, 45*(4), 222-228.

OECD. (2018). *The future of education and skills: Education 2030: the future we want*. Paris, France: OECD.

Ofodile, U. C., & Mankilik, M. (2015). Development and validation of a hybrid active learning strategy for teaching direct current electricity concepts for secondary schools in Nigeria. *International Journal for Innovation Education and Research, 3*(8), 56-66.

Okebukola, P. (2012). *Breaking the barriers to national development: are we taking full advantage of science and technology*. 19th and 20th convocation lecture. Federal University of Technology Minna.

Okoli, C., & Pawlowski, S. D. (2004). The Delphi method as a research tool: an example, design considerations and applications. *Information & Management, 42*(1), 15-29.

Okwoufu, O. (2014). ASUU, others demand state of emergency in education. *The nation Newspapers 3rd November*. Retrieved from http://thenationonlineng.net/asuu-others-demand-state-of-emergency-in-education/

Olayinka, A.-R. B. (2016). Effects of instructional materials on secondary schools students' academic achievement in social studies in Ekiti state, Nigeria. *World Journal of Education, 6*(1), 32-39.

Olivarez, N. (2012). *The impact of a STEM program on academic achievement of eighth grade students in a South Texas middle school.* (Ph.D), Texas A & M University - Corpus Christi, UMI dissertation publishing. (UMI3549798)

Olszewski-Kubilius, P. (2010). Special schools and other options for gifted STEM students *Roeper Review, 32*, 61-70.

Omilani, N. A., Akinyele, S. A., Durowoju, T. S., & Obideyi, E. I. (2018). The effect of the assessment of practical-based work on pupils' problem solving and achievement in Basic Science and Technology in Odeda local government of Ogun State, Nigeria. *Education 3-13*, 1-13.

Oonsim, W., & Chanprasert, K. (2017). Developing critical thinking skills of grade 11 students by STEM education: A focus on electrostatic in physics. *Rangsit Journal of Educational Studies, 4*(1), 54-59.

Osman, K., Hiong, L. C., & Vebrianto, R. (2013). 21st Century biology: An interdisciplinary approach of biology, technology, engineering and mathematics education. *Procedia - Social and Behavioral Sciences, 102*, 188-194.

Osman, K., & Saat, R. M. (2014). Editorial Science Technology, Engineering and Mathematics (STEM) education in Malaysia. *EURASIA Journal of Mathematics, Science & Technology Education, 10*(3), 153-154.

Otis, K. (2010). Top 5-benefits of hands-on learning environment. Retrieved from http://news.everest.edu/post2010/01/top5-benefits-of-a-hands-on-learningenvironment/#,UkEthyWTD91Y.

Oyelekan, O. S., Igbokwe, E. F., & Olorundare, A. S. (2017). Science teachers' utilisation of innovative strategies for teaching senior school science in Ilorin, Nigeria. *Malaysian Online Journal of Educational Sciences, 5*(2), 49-65.

P21. (2015). Framework for 21st century learning. The partnership for 21st century skills. http://www.p21.org/about-us/p21-framework.

Pallant, A., Pryputniewicz, S., & Lee, H. S. (2012). Exploring the unknown. *The Science Teacher, 79*(3), 60-65.

Park, M. (2008). Implementing curriculum integration: the experiences of Korean elementary teachers. *Asia Pacific Education Review, 9*(3), 308-319.

Pascarella, E. T., Wang, J.-S., Trolian, T. L., & Blaich, C. (2013). How the instructional and learning environments of liberal arts colleges enhance cognitive development. *Higher Education, 66*(5), 569-583.

Patel, N. (2010). Gagan Goyal: Roboteacher :Gagan Goyal believes that complex concepts in mathematics, science, technology and engineering are best taught through hands-on learning. India Today. Retrieved from http://indiatoday. intoday.in/story/gagan-goyal-roboteacher/1/113845 .html.

Patton, M. Q. (2002). *Qualitative evaluation and research methods*. Thousand Oaks: CA: Sage Publications, Inc.

Paul, R. (2004). The state of critical thinking today: as the organizer in developing blueprints for institutional change. Retrieved from http://www. criticalthinking.org/professionalDev/the-state-cttoday.cfm. Retrieved from

Pellegrino, J. W. (2014). Assessment as a positive influence on 21st century teaching and learning: A systems approach to progress. *Psicología Educativa, 20*(2), 65-77.

Peterson, C. (2003). Bringing ADDIE to life: Instructional design at its best. *Journal of Educational Multimedia and Hypermedia, 12*(3), 227-241.

Petroski, H. (2010). Occasional design. *American Scientist, 98*(1), 16-19.

Phonchaiya, S. (2014). STEM and advanced thinking. *IPST Magazine, 42*(189), 7-10.

Piaw, C. Y. (2010). Building a test to assess creative and critical thinking simultaneously. *Procedia - Social and Behavioral Sciences, 2*(2), 551-559.

Piaw, C. Y. (2012). *Mastering research method*. Shah Alam: Malaysia: McGraw-Hill Education Snd. Bhd.

Piaw, C. Y. (2013). *Mastering research statistics*. Shah Alam, Malaysia: McGraw-Hill Education Snd. Bhd.

Pickering, D. (2010). Teaching the thinking skills that higher-order tasks demand. In R. Marzano (Ed.), *On excellence in teaching*. Bloomington, IN: Solution Tree Press.

Pitan, O. S., & Adedeji, S. O. (2012). Skills mismatch among university graduates in the nigeria labor market. *US-China Education Review A 1 (2012) 90-98, A*(1), 90-98.

Pitkäniemi, H., & Vanninen, P. (2012). Learning attainments as a result of student activity, cognition and the classroom environment. *Problems of Education in the 21St Century, 41*, 75-86.

Polit, D. F., & Beck, C. T. (2006). The content validity index: are you sure you know what's being reported? Critique and recommendations. *Research in Nursing & Health, 29*(5), 489–497.

Powell, K. C., & Kalina, C. J. (2009). Cognitive and social constructivism: Developing tools for an effective classroom. *Education, 130*(2), 141-250.

Prayitno, B. A., Suciati, & Titikusumawati, E. (2019). Enhancing students' Higher order thinking Skills in science through Instad strategy. *Journal of Baltic Science Education, 17*(6), 1046-1055.

Preus, B. (2012). Authentic instruction for 21st-century learning: Higher order thinking in an inclusive school. *American Secondary Education, 40*(3), 59-79.

Prinsley, R., & Baranyai, K. (2015). *STEM skills in the workforce: what do employers want?* : Occasional Papers Series, Office of the Chief Scientist.

Punch. (2014, 29, March). Teaching without learning in Nigerian schools. *Punch Newspapers*.

Purzer, S., & Shelley, M. (2018). The rise of engineering in STEM education: The E in STEM. In M. Shelley & S. A. Kiray (Eds.), *Research highlights in STEM education* (pp. 38-56). Iowa, USA: ISRES Publishing.

Pytel, B. (2013). Hands-on science more effective: Nations that surpass the US in science teach students a different method. They don't teach out of a book... the methods are hands-on Retrieved from http://suit101.com/ahandsonscience-more-effective-a45673

Raes, A., Schellens, T., & De Wever, B. (2013). Web-based collaborative inquiry to bridge gaps in secondary science education. *The Journal of the Learning Sciences, 23*(3), 316-347.

Ramalingam, S. T. (2005). *Modern Biology, Senior Secondary Science Series. New Edition*. Onitsa: African Feb Publishres.

Ramos, J. L. S., Dolipas, B. B., & Villamor, B. B. (2013). Higher order thinking skills and academic performance in physics of college students: A regression analysis. *International Journal of Innovative Interdisciplinary Research, 4*, 48-60.

Rauf, R. A. A., Rasul, M. S., Sathasivam, R., & Rahim, S. A. (2017). Training of trainers STEM build program for primary science teachers: An initiative towards STEM education in schools. In Pixel (Ed.), *International Conference New Perspectives in Science Education*. Florence, Italy: libreriauniversitaria.it Edizioni.

Razali, N. M., & Wah, Y. B. (2011). Power comparisons of Shapiro-Wilk, Kolmogorov-Smirnov, Lilliefors and Anderson-Darling tests. *Journal of Statistical Modeling and Analytics, 2*(1), 21-33.

Reeve, E. M. (2013). Implementing Science, Technology, Mathematics, and Engineering (STEM) education in Thailand and in ASEAN. *A report prepared for: The institute for the promotion of teaching science and technology (IPST)*. Retrieved from http://dpst-apply.ipst.ac.th/specialproject/images/IPST_Global/document/Implementing%20STEM%20in%20ASEAN%20%20-%20IPST%20May%207%202013%20-%2

Riskowski, J. L., Todd, C. D., Wee, B., Dark, M., & Harbor, J. (2009). Exploring the effectiveness of an interdisciplinary water resources engineering module in an eight grade science course. *International journal of Engineering Education, 25*(1), 181-195.

Roberts, A. (2012). A justification for STEM education. The Technology and Engineering. *Teacher Online, 71*(8), 1-4.

Robinson, A., Dailey, D., Hughes, G., & Cotabish, A. (2014). The effects of a science-focused STEM intervention on gifted elementary students' science knowledge and skills. *Journal of Advanced Academics, 25*(3), 189-213.

Rockland, R., Bloom, D. S., Carpinelli, J., Burr-Alexander, L., Hirsch, L. S., & Kimmel, H. (2010). Advancing the "E" in K-12 STEM education. *The Journal of Technology studies, 36*(1), 53-64.

Roehrig, G. H., Moore, T. J., Wang, H.-H., & Park, M. S. (2012). Is adding the E enough? Investigating the impact of K-12 engineering standards on the implementation of STEM integration. *School Science and Mathematics, 112*(1), 31-44.

Romli, S., Abdurrahman, & Riyadi, B. (2018). Designing students' worksheet based on open-ended approach to foster students' creative thinking skills. *Journal of Physics: Conference Series, 948*, 1-6.

Roth, W. M. (1992). Bridging the Gap between school and real life: Toward an integration of science, mathematics, and technology in the context of authentic practice. *School Science and Mathematics, 92*(6), 307-317.

Ruggiero, V. R. (2012). *The art of thinking: A guide to critical and creative thought* (10 ed.). New York, NY: Longman.

Saat, R. M. (2003). *Learning primary science in a web-based learning environment.* (Ph.D), Unpublished doctoral Thesis Universiti Putra Malaysia,

Sada, A. M., Mohd, Z. A., Adnan, A., & Yusri, K. (2016). Prospects of problem-based learning in building critical thinking skills among technical college students in Nigeria. *Mediterranean Journal of Social Sciences, 7*(3), 256-265.

Sahin, A., Ayar, M. C., & Adiguzel, T. T. (2014). STEM related after-school program activities and associated outcomes on student learning educational sciences. *Theory & Practice, 14*(1), 309-322.

Saido, G. M., Siraj, S., Nordin, A. B. B., & Al_Amedy, O. S. (2015). Higher order thinking skills among secondary school students in science learning. *The Malaysian Online Journal of Educational Science, 3*(3), 13-20.

Salami, C. G. E. (2013). Youth unemployment in Nigeria: A time for creative intervention. *International Journal of Business and Marketing Management, 1*(2), 18-26.

Salinger, G., & Zuga, K. (2009). The overlooked STEM imperatives: Technology and engineering. In I. I. T. a. E. E. Association (Ed.), *Background and history of the STEM movement* (pp. 4-9). Reston, VA: ITEEA.

Sampurno, P. J., Sari, Y. A., & Wijaya, A. D. (2015). Integrating STEM (Science, Technology, Engineering, Mathematics) and Disaster (STEM-D) education for building students' disaster literacy. *International Journal of Learning and Teaching, 1*(1), 73-76.

Sanders, M. (2009). STEM, STEM education, STEMania. *The Technology Teacher, 48*(4), 20-26.

Santos, P. (2016). Teaching critical thinking skills in a disciplinary context. *Contact Magazine, 42*(3), 46-51.

Saputri, A. C., Sajidan, S., Rinanto, Y., Afandi, A., & Prasetyanti, N. M. (2019). Improving students' critical thinking skills in cell-metabolism learning using stimulating higher order thinking skills model. *International Journal of Instruction, 12*(1), 327-342.

Saraç, H. (2018). The effect of Science, Technology, Engineering and Mathematics-Stem educational practices on students' learning outcomes: A meta-analysis study. *The Turkish Online Journal of Educational Technology, 17*(2), 125-142.

Sasson, I., Yehuda, I., & Malkinson, N. (2018). Fostering the skills of critical thinking and question-posing in a project-based learning environment. *Thinking Skills and Creativity, 29*, 203-212.

Satchwell, R. E., & Loepp, F. L. (2002). Designing and implementing an integrated mathematics, science, and technology curriculum for middle school. *Journal of Industrial Teacher Education, 39*(3), 41-66.

Satterthwait, D. (2010). Why are 'hands-on' science activities so effective for student learning? *Teaching Science: The Journal of the Australian Science Teachers Association, 56*(2), 7-10.

Savery, J. R. (2006). Overview of problem-based learning: Definitions and distinctions. *Interdisciplinary Journal of Problem-Based Learning, 1*(1), 9-20.

Saxton, E., Burns, R., Holveck, S., Kelley, S., Prince, D., Rigelman, N., & Skinner, E. A. (2014). A common measurement system for K-12 STEM education: Adopting an educational evaluation methodology that elevates theoretical foundations and systems thinking. *Studies in Educational Evaluation, 40*, 18-35.

Schlechty, S. (2011). STEM education: Time for integration. *Peer Review, 13*(3), 4-7.

Schofield, J. W. (2010). International evidence on ability grouping with curriculum differentiation and the achievement gap in secondary schools. *Teachers College Record, 112*(5), 1492–1528.

Schreiber, L. M., & Valle, B. E. (2013). Social constructivist teaching strategies in the small group classroom. *Small Group Research, 44*(4), 395-411.

Schulz, H. W., & FitzPatrick, B. (2016). Teachers' understandings of critical and higher order thinking and what this means for their teaching and assessments. *Alberta Journal of Educational Research, 62*(1), 61–86.

Seels, B., & Glasgow, Z. (1998). *Making instructional design decisions* (2nd ed.). Upper Saddle River, NJ: Merrill/Prentice Hall.

Seimears, C. M., Graves, E., Schroyer, M. G., & Staver, J. (2012). How constructivistbased teaching influences students learning science. *The Educational Forum, 72*(2), 265-271.

Sekaran, U., & Bougie, R. (2010). *Research methods for business: A skill building approach*. New York, NY: John Willey & Sons.

Shah, C. G. (2010). Critical Thinking. What it is and why it matters to emerging professionals? . *Advanced Materials and Processes, 168*(5), 66-69.

Shahali, E. H. M., Halim, L., Rasul, M. S., Osman, K., & Zulkifeli, M. A. (2017). STEM learning through engineering design: Impact on middle secondary students' interest towards STEM. *EURASIA Journal of Mathematics, Science and Technology Education, 13*(5), 1189-1211.

Shaughnessy, M. F. (2012). *Critical thinking and higher order thinking: A current perspective*. Hauppauge, NY: Nova Science Publishers.

Shernoff, D. J., Sinha, S., Bressler, D. M., & Ginsburg, L. (2017). Assessing teacher education and professional development needs for the implementation of integrated approaches to STEM education. *Int J STEM Educ, 4*(13), 1-16.

Siegel, H. (1988). *Educating reasiob*. New York: Routledge.

Sinatra, G. M., Heddy, B. C., & Lombardi, D. (2015). The challenges of defining and measuring student engagement in science. *Educational Psychologist, 50*(1), 1-13.

Siter, S., Klahr, D., & Matlen, B. (2013). Conceptual Change in Experimental Design: From Engineering Goal to Science Goals. In S. Vosniadou (Ed.), *Hanbook of Research on Conceptual Change* (2 ed.). Anthens: Routledge.

Slavin, R. E. (1990). Achievement effects of ability grouping in secondary schools: A best-evidence synthesis. *Review of Educational Research, 60*(3), 471-499.

Slavin, R. E. (1993). Ability grouping in the middle grades: Achievement effects and alternatives. *The elementary school journal, 93*(5), 535–552.

Smith, P. L., & Regan, T. J. (1999). *Instructional design*. New York NY: Willey.

STAN. (2004). *Biology for Senior Secondary Schools. Revised Edition*. Ibadan: Heinemann.

Stapleton, P. (2011). A survey of attitudes towards critical thinking among Hong Kong secondary school teachers: Implications for policy change. *Thinking Skills and Creativity, 6*, 14–23.

Starko, A. J. (2004). *Creativity in the classroom: Schools of curious delight*. New York: Routledge.

Sternberg, R. J. (1984). How can we teach intelligence? *Educational Leadership*, 38-48.

Stewart, J. (1982). Difficulties experience by high school students when learning basic Mendelian genetics *The American Biology Teacher, 44*(2), 80-89.

Stohlmann, M., Moore, T., McClelland, J., & Roehrig, G. (2011). Impressions of a middle grades STEM integration program: Educators share lessons learned from the implementation of a middle grades STEM curriculum model. *Middle School Journal, 43*(1), 32-40.

Stohlmann, M., Moore, T., & Roehrig, G. H. (2012). Considerations for teaching integrated STEM education. *Journal of Pre-College Engineering Education Research, 2*(1), 28-34.

Strauss, A., & Corbin, J. (1990). *Basics of qualitative research: Grounded theory procedures and technique*. Newbury Park, CA: Sage.

Stuckey, H. (2014). The first step in Data Analysis: Transcribing and managing qualitative research data. *Journal of Social Health and Diabetes, 02*(01), 6-8.

Styron Jr, R. A. (2014). Critical thinking and collaboration: A strategy to enhance student learning. *systemics, Cybernetics and Informatics, 12*(7), 25-30.

Sullivan, G. M., & Feinn, R. (2012). Using effect size-or why the p-value Is not enough. *J Grad Med Educ, 4*(3), 279-282.

Symonds, W. C., Schwartz, R. B., & Ferguson, R. (2011). *Pathways to prosperity: Meeting the challenge of preparing young Americans for the 21st century*. Cambridge, MA:: Harvard Graduate School of Education.

Taber, K. S. (2010). Challenging gifted learners: General principles for science educators; and exemplification in the context of teaching chemistry. *Science Education International, 21*(1), 5-30.

Taleb, H. M., & Chadwick, C. (2016). Enhancing students critical thinking skill and analitycal thinking skill at the higher education level in developing countries: Case study in Dubai. *Journal of Education and Instructional Studies in the World, 6*(1), 67-77.

Tayyeb, R. (2013). Effectiveness of problem based learning as an instructional tool for acquisition of content knowledge and promotion of critical thinking among medical students. *Journal ot the College of Physicians and Surgeons Pakistan, 23*(1), 42-46.

TEAL. (2013). TEAL Center Fact Sheet No. 12: Deeper Learning through Questioning. 1-5.

Tekkaya, C., Ozkan, O., & Sunkur, S. (2001). Biology concepts perceived as difficult by Turkish high school students. *Hacettepe Üniversitesi Eğitim Fakültesi Dergisi, 21*, 145-150.

Temel, S. (2014). The effects of problem-based learning on pre-service teachers' critical thinking dispositions and perceptions of problem-solving ability. *South African Journal of Education, 34*(1), 1-20.

Teo, P. (2019). Teaching for the 21st century: A case for dialogic pedagogy. *Learning, Culture and Social Interaction, 21*, 170-178.

Texas Education Agency. (2009). Texas assessment of knowledge and skills performance.

Thaiposri, P., & Wannapiroon, P. (2015). Enhancing students' critical thinking skills through teaching and learning by inquiry-based learning activities using social network and cloud computing. *Procedia - Social and Behavioral Sciences, 174*, 2137-2144.

Thalib, M., Corebima, A. D., & Ghofur, A. (2017). Comparison on critical thinking skill and cognitive learning outcome among students of X grade with high and low academic ability through reading questioning answering (RQA) strategy. *Jurnal Pendidikan Sains, 5*(1), 26-31.

the NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington DC: National Academy Press.

Thibaut, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., . . . Depaepe, F. (2018a). Integrated STEM education: A systematic review of instructional practices in secondary education. *European Journal of STEM Education, 3*(1), 1-12.

Thibaut, L., Knipprath, H., Dehaene, W., & Depaepe, F. (2018b). The influence of teachers' attitudes and school context on instructional practices in integrated STEM education. *Teaching and Teacher Education, 71*, 190-205.

Thomas, G. P., & Anderson, D. (2014a). Changing the metacognitive orientation of a classroom environment to enhance students' metacognition regarding chemistry learning. *Learning Environments Research, 17*(1), 139-155.

Thomas, G. P., & Anderson, D. (2014b). Changing the metacognitive orientation of a classroom environment to enhance students' metacognition regarding chemistry learning. *Learning EnvironmentsResearch,17, 139–155, 17*, 139-155.

Thomas, M. E. (2013). *The effects of an integrated S.T.E.M. Curriculum in fourth grade students' mathematics achievement and attitudes* (PHD), Trevecca Nazarene University, Nashville, ProQuest LLC (2013). Retrieved from https://search.proquest.com/docview/1413329612?Accountid=7374 (UMI 3565696)

Tiimner, W., E., Chapman, J. W., Greaney, K. T., & Prochnow, J. E. (2002). The contribution of educational psychology to intervention research and practice. *International Journal o f Disability, Development and Education, 49*(1), 11-29.

Tiruneh, D. T., De Cock, M., Weldeslassie, A. G., Elen, J., & Janssen, R. (2017). Measuring critical thinking in physics: development and validation of a critical thinking test in electricity and magnetism. *International Journal of Science and Mathematics Education, 15*(4), 663–682.

Tiruneh, D. T., Gu, X., De Cock, M., & Elen, J. (2018). Systematic design of domain-specific instruction on near and far transfer of critical thinking skills. *International Journal of Educational Research, 87*, 1-11.

Tiruneh, D. T., Verburgh, A., & Elen, J. (2014). Effectiveness of critical thinking instruction in higher education: a systematic review of intervention studies. *Higher Education Studies, 4*(1), 1-17.

Toma, R. B., & Greca, I. M. (2018). The effect of integrative STEM instruction on elementary students' attitudes toward science. *EURASIA Journal of Mathematics, Science and Technology Education, 14*(4), 1383-1395.

Tomkin, J. H., Beilstein, S. O., Morphew, J. W., & Herman, G. L. (2019). Evidence that communities of practice are associated with active learning in large STEM lectures. *International Journal of STEM Education, 6*(1), 1-15.

Toomela, A., Kikas, E., & Mõttus, E. (2006). Ability grouping in schools: A study of academic achievement in five schools in estonia *TRAMES, 10*(1), 32–43.

Treacy, P., & O'Donoghue, J. (2014). Authentic integration: A model for integrating mathematics and science in the classroom. *International Journal of Mathematical Education in Science and Technology, 45*(5), 703-718.

Tsui, C.-Y., & Treagust, D. F. (2010). Evaluating secondary students' scientific reasoning in genetics using a two-tier diagnostic instrument. *International Journal of Science Education, 32*(8), 1073-1098.

Tsui, C., & Treagust, D. F. (2002). *A preservice teachers pedagogical content knowledge (PCK). The story of Linda.* Paper presented at the Australian Association for Research in Education (AARE) Conference, Brisbane, Queensland, Australia. http://ccmsncache.com

Tsui, C. Y., & Treagust, D. F. (2007). Understanding genetics: Analysis of secondary students conceptual status. *Journal of research in science teaching, 44*(2), 205-235.

Tsui , L. (1999). Courses and instruction affecting critical thinking. *Research in Higher Education, 40*(2), 185-200.

Tsupros, N., Kohler, R., & Hallinen, J. (2009). STEM education: A project to identify the missing components, Intermediate Unit 1 and Carnegie Mellon University, Pittsburgh, PA.

Tucker, S. (2007). Using remark statistics for test reliability and item analysis. Retrieved from: http://www.umaryland.edu/cits/testscoring/pdf/umbtestscoring_testanditemanalysis.pdf.

Tuckman, B. W. (1999). *Conducting educational research* (5 ed.). Fort Worth TX: Harcourt Brace.

Tytler, R., & Osborne, J. (2012). Student attitudes and aspirations towards science. In B. J. Fraser, K. Tobin, & C. J. McRobbie (Eds.), *Second international handbook of science education* (pp. 597-625). New York, NY: Springer International.

Udeani, U., & Adeyemo, S. A. (2011). The relationship among teachers' problem solving abilities, student's learning styles and students' Aachievement in biology. *International Journal of Educational Research and Technology, 2*(1), 82-87.

Umar, A. A. (2011). Effects of biology practical activities on students' process skill acquisition in Minna, Niger State, Nigeria. . *Journal of Science, Technology, Mathematics and Education,, 7*(2), 118-126.

Usman, I. A. (2010). Investigation into the effects of discovery methods of instruction of the academic achievement in genetics among collage of education in north western Nigeria. *Journal of Science, Technology, Mathematics and Education (JOSTMED), 7*(1), 120-126.

VanTassel-Baska, J., Zuo, L., Avery, L. D., & Little, C. A. (2002). A curriculum study of gifted-student learning in the language arts. *Gifted Child Quarterly, 46*, 30-44.

Vasquez, J., Sneider, C., & Comer, M. (2013). *STEM lesson essentials, grades 3–8: integrating science, technology, engineering, and mathematics*. Portsmouth, NH: Heinemann.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes* Cambridge: MA: Harvard University Press.

Wade, C. (1995). Using writing to develop and assess critical thinking. *Teaching of Psychology, 22*(1), 24-28.

Wagner, T. (2008). *The global achievement gap: Why even our best schools don't teach the new survival skills our children need and what we can do about it.* New York: NY: Basic Books.

Walker, W. S., Moore, T. J., Guzey, S. S., & Sorge, B. H. (2018). Frameworks to develop integrated STEM curricula. *K-12 STEM Education, 4*(2), 331-339.

Wallace, J., Malone, J., Rennie, L., Budgen, F., & Venville, G. (2001). The rocket project: an interdisciplinary activity for low achievers. *Aust Math Teach., 57*(1), :6–11.

Wang, H. (2012). *A new era of science education: Science teachers' perceptions and classroom practices of science, technology, engineering, and mathematics (STEM) integration.* (Ph.D), University of Minnesota,

Wang, H., Moore, T. J., Roehrig, G. H., & Park, M. S. (2011). STEM integration : Teacher perceptions and practice. *Journal of Pre-College Engineering Education Research, 1*(2), 1-13.

Warner, R. M. (2013). *Applied statistics: From bivariate through multivariate techniques*. Thousand Oaks, CA: SAGE Publications.

Watson, G., & Glaser, E. M. (1980). *Watson-Glaser critical thinking appraisal manual*. San Antonio, TX: The Psychological Corporation.

Watson , G., & Glaser, E. M. (1991). *Watson-Glaser critical thinking appraisal: British Manual*. London: The Psychological Corporation Ltd.

Watson, G., & Glaser, E. M. (2008). *Watson-Glaser critical thinking appraisal: Forms A and B manual*. Upper Saddle River, NJ: Pearson Education.

Watson, G., & Glaser, E. M. (2010). *Watson-Glaser II Critical Thinking Appraisal®*. USA: NCS Pearson.

Weber, J. R. (2014). A problem-based learning helps bridge the gap between the classroom and the real world. Retrieved from http://www.facultyfocus.com/articles/instructionaldesign/problem-based-learning-helps-bridge-gap-classroom-real-world/.

Wells, J. G. (2016). Efficacy of the technological/engineering design approach: Imposed cognitive demands within design-based biotechnology instruction. *Journal of Technology Education, 27*(2), 4-20.

Wendell, K. B., & Rogers, C. (2013). Engineering design-based science, science content performance, and science attitudes in elementary school. *Journal of Engineering Education, 102*(4), 513-540.

West African Examination Council (2007). [May/June, Chief Examiner's Report].

West, M. (2012). *STEM education and the workplace*. Retrieved from Retrieved 1 July 2013 from www.chiefscientist.gov.au/2012/09/stem-education-and-the-workplace/

Williams, J. (2011). STEM education: Proceed with caution. *Design and Technology Education, 16*(1), 26-35.

Williams , M., DeBarger, A. H., Montgomery, B. L., Zhou, X., & Tate, E. (2012). Exploring middle school students' conceptions of the relationship between genetic inheritance and cell division. *Science Education, 96*(1), 78-103.

Williams, M., Montgomery, B. L., & Manokore, V. (2012). From phenotype to genotype: Exploring middle school students' understanding of genetic inheritance in a web-based environment. *The American Biology Teacher, 74*(1), 35-40.

Willingham, D. T. (2007). Critical thinking: Why is it so hard to teach? *Arts Education Policy Review, 109*, 21-29.

Woehlke, P. L. (1985). Watson-Glaser critical thinking appraisal In D. J. Keyser & R. C. Sweetland (Eds.), *Test Critiques* (Vol. III, pp. 682-685). Kansas City, MO: Test Corporation of America.

Yahya, A. A., Toukal, Z., & Osman, A. (2012). *Bloom's taxonomy-based classification for item bank questions using support vector machines. In modern advances in intelligent systems and tools*. Berlin, Germany: Springer.

Yaki, A. A., & Babagana, M. (2016). Technology instructional package mediated instruction and senior secondary school students' academic performance in biology concepts. *The Malaysian Online Journal of Educational Science, 4*(2), 42-48.

Yaki, A. A., Saat, R. M., Sathasivam, R. V., & Zulnaidi, H. (2019). Enhancing science achievement utilising an integrated STEM approach. *Malaysian Journal of Learning and Instruction, 16*(1), 181-205.

Yang, Y., Van Aalst, J., Chan, C. K. K., & Tian, W. (2016). Reflective assessment in knowledge building by students with low academic achievement. *International Journal of Computer-Supported Collaborative Learning, 11*(3), 281-311.

Yildirim, B., & Özkahraman, Ş. (2011). Critical thinking theory and nursing education. *International Journal of Humanities and Social Science, 1*(17), 176-185.

Yıldırım, B., & Sidekli, S. (2017). STEM applications in mathematics education: The effect of STEM applications on different dependent variables. *Journal of Baltic Science Education, 17*(2), 200-214.

Yildirim, N., Kurt, S., & Ayas, A. (2011). The effect of the worksheets on students' achievement in chemical equilibrium. *Journal of Turkish Science Education, 8*(3), 44-58.

Yu, W. F., She, H. C., & Lee, Y. M. (2010). The effects of web-based/non-web-based problem-solving instruction and high/low achievement on students' problem-solving ability and biology achievement. *Innovations in Education and Teaching International, 47*(2), 187-199.

Yuan, S., Liao, H., & Wang, Y. (2014). Developing of a scale to measure the critical thinking disposition of medical care professional 42(2), 303-312. *Social Behavior and Personality, 42*(2), 303-312.

Zachariades, T., Christou, C., & Pitta-Pantazi, D. (2013). Reflective, systemic and analytic thinking in real numbers. *Educational Studies in Mathematics, 82*(1), 5-22.

Zady, M. F., Portes, P. R., & Ochs, V. D. (2003). Examining classroom interactions related to difference in students' science achievement. *Science Education, 87*(1), 40-63.

Zeluff, J. (2011). *Hands-on learning and problem based learning are critical methods in aiding student understanding of alternative energy concepts.* (Doctoral dissertation), Michigan State University, UMI ProQuest LLC.

Zhbanova, K. S., Rule, A. C., Montgomery, S. E., & Nielsen, L. E. (2010). Defining the difference: comparing integrated and traditional single-subject lessons. *Early Childhood Education Journal, 38*(4), 251-258.

Zhou, Q., Huang, Q., & Tian, H. (2013). Developing students' critical thinking skills by task-based learning in chemistry experiment teaching. *Creative Education, 4* (12A ), 40-45.

Zimmerman, H., & Land, S. M. (2014). Facilitating place-based learning in outdoor informal environments with mobile computers. *Techtrends: Linking Research & Practice to Improve Learning, 58*(1), 77-83.

Zohar, A., & Peled, B. (2008). The effects of explicit teaching of metastrategic knowledge on low- and high-achieving students. *Learning and Instruction, 18*(4), 337-353.

Zohar, A., & Tamir, P. (1993). Incorporating critical thinking into a regular high school biology curriculum. *School Science and Mathematics, 93*, 136-140.

Zulmaulida, R., Wahyudin, & Dahlan, J. A. (2018). Watson-Glaser's critical thinking skills. *Journal of Physics: Conference Series, 1028*, 1-6.