RELATIVE SUSCEPTIBILITY OF SELECTED MAIZE SEED VARIETIES TO THE MAIZE WEEVIL (*Sitophilus zeamais* Motschulsky) IN GHANA

BY

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DECLARATION

I, Acheampong Anthony, hereby declare that except for the references to work of other researchers which have been duly cited, this thesis consists entirely of my original research work and that no part of it has been presented for another degree in this university or elsewhere.

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ABSTRACT

Studies were carried out under ambient laboratory conditions of 25 ± 2°C and 70 ± 5% relative humidity to determine the relative susceptibility of eighteen maize seed varieties to attack by the maize weevil, *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae). The experiment was laid out in a Completely Randomized Design (CRD), with eighteen maize varieties replicated three times. Adult mortality, number of F_1 progeny, weevil development time, susceptibility index, seed damage, seed weight loss, and weight of powder/frass produced were determined after storage period of three months. The susceptibility index was determined using Dobie's formula and the varieties were classified into different reaction groups. The varieties exhibited varying degrees of susceptibility to *S. zeamais* attack. Only Aseda was regarded as resistant and TZE-Y POP STR as moderately resistant to *S. zeamais*. Kpari-Faako, Tintim, WACCI-M-1215, WACCI-M-1594 and Wang-Dataa were regarded as moderately susceptible to *S. zeamais*. However, Abontem, Bihilifa, Ewul-Boyu, Sanzal-Sima, TZE-I 17, WACCI-M-1205, WACCI-M-1508 and WACCI-M-1510 were regarded as susceptible varieties. Furthermore, Aburohemaa, Obaatanpa and Omankwa were regarded as highly susceptible to *S. zeamais*. Index of susceptibility (IS) had significant and positive association with the number of F_1 progeny ($r = 0.9$, $P<0.001$), seed damage ($r = 0.9$, $P<0.001$), seed weight loss ($r = 0.6$, $P<0.001$), weight of frass produced ($r = 0.9$, $P<0.001$) and seed moisture content ($r = 0.3$, $P<0.024$). However, an inverse association existed between the IS and adult mortality ($r = -0.4$, $P<0.005$), median development period ($r = -0.5$, $P<0.001$) and seed germination ($r = -0.7$, $P<0.001$). The use of insect resistant varieties would offer a sustainable way of minimizing postharvest losses of seeds in storage especially for smallholder farmers who keep harvested grains for future use as food and seed.

DEDICATION

This project work is dedicated to Professor John Kwasi Anarfi and all those seeking knowledge in insect science. Hopefully, they will find the study of insects as exciting as I do.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
CABI	Centre for Agriculture and Bioscience International
CAT	Controlled Atmosphere Technique
CIMMYT	Centro Internacional de Mejoramiento de Maíz y Trigo
CRD	Completely Randomized Design
CRI	Crops Research Institute
CV	Coefficient of Variation
DAP	Days after planting
DAS	Days after set up
DFE	Date of first emergence
DTMA	Drought Tolerance Maize for Africa
F_1P	First filial progeny
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Statistics
g	Gramme
GGDP	Ghana Grains Development Project
GHz	Gigahertz
Gy	Gray

h	Hour
HPR	Host Plant Resistance
IITA	International Institute of Tropical Agriculture
IPM	Integrated Pest Management
IS	Index of Susceptibility
kg	Kilogramme
kW	Kilowatts
L	Litre
Ln	Natural logarithm
LSD	Least Significant Difference
MA	Modified Atmosphere
MDP	Median Development Period
mg	Milligramme
mL	Millilitre
mm	Millimetre
MoFA	Ministry of Food and Agriculture
Mor	Mortality
MT/Ha	Metric tonnes per hectare

OECD	Organization for Economic Co-operation and Development
OPV	Open-Pollinated Variety
RH	Relative humidity
SARI	Savanna Agricultural Research Institute
SD	Seed damage
SG	Seed germination
SMC	Seed moisture content
SRID	Statistical Research and Information Department
SWL	Seed weight loss
WACCI	West Africa Centre for Crop Improvement

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Maize (*Zea mays* L.) is an essential component of global food security. Maize serves as a valuable cereal crop in the world due to its diverse use as food for man, feed for livestock and raw material for several industries (Gupta *et al*., 2015). It is one of the most commonly grown crops and a major staple crop for many smallholder farmers in the world. The crop has diverse germplasm adapted to different ecological zones (Koutsika-Sotiriou, 1999). Maize is predominantly grown by small-scale farmers and is a major staple in many countries of Africa.

In Ghana, it is the principal staple crop produced and consumed by most farming households. Maize has nearly replaced traditional staple crops like sorghum and pearl millet in Ghana particularly in the Northern Region (Statistical Research and Information Department of the Ministry of Food and Agriculture [SRID-MoFA], 2011). Maize is the most cultivated crop in Ghana, and 2.6 metric tonnes of the crop is produced annually (Organization for Economic Co-operation and Development [OECD], 2016). Hence it is ranked first among cereal crops in the country in terms of area planted and value of sales (Ministry of Food and Agriculture [MoFA], 2014). Maize is grown in almost every region in Ghana. The five major maize growing areas in Ghana are the Eastern, Ashanti, Central, Brong Ahafo and the Northern Regions (Adu *et al*., 2014). The system of maize cultivation differs among these growing areas (Morris *et al*., 1999).

1.2 Problem Statement

Despite the efforts made in increasing production and productivity of maize through the development of high yielding stress tolerant varieties in the country there is evidence of seed and food insecurity arising from high storage losses. In Africa, the storage of grains for used as food and seed for future planting is commonly practiced by smallholder farmers. However, preservation of the quality of the grain is a major drawback during long-term storage (Tefera *et al*., 2011a). In Ghana, it is reported that most farmers experience very high storage losses of 40% during the minor season and 20% to 30% during the major season (Opit *et al*., 2014). One of the factors responsible for the high storage losses is the problem of stored grain insect pests, including the maize weevil, *Sitophilus zeamais* (Motschulsky); rice weevil, *S. oryzae* (L.); Angoumois grain moth, *Sitotroga cerealella* (Olivier); and the larger grain borer, *Prostephanus truncatus* (Horn) (Abebe *et al*., 2009; Bekele *et al*., 1995; Dobie, 1977; Hodges, 2012; Tefera *et al*., 2011a).

High storage losses experienced by smallholder farmers threaten their livelihoods in Africa (Kamanula *et al*., 2011). The maize weevil affects the crop prior to harvest and multiplies further after storage (Caswell, 1962; Demissie *et al*., 2008). Storage loss of 20% – 90% due to *S. zeamais* for untreated maize has been reported by Giga *et al*. (1991) and Muzemu *et al*. (2013). It is a serious pest of maize in tropical regions, causing huge losses to many small-scale farmers who keep grains on farm for future use as food and seed (Thanda and Kevin, 2003). The latter accounts for almost 80% of the seed needs of smallholder farmers (Louwaars and De Boef, 2012). Existing control measures for stored product insect pests include sanitation, modification of the storage environment, chemical pesticides, biological control and host plant resistance (Golob, 2002). Of these existing control measures, the application of chemical pesticides is the most common insect pest management strategy among farmers in rural communities. These chemical pesticides are expensive and farmers lack requisite skills to handle and use them (Rugumamu, 2011). Additionally, their widespread use lead to environmental hazards, development of resistance, bioaccumulation and adversely affect non-target organisms (Dhuyo and Ahmed, 2007). Ecologically friendly stored-product control methods are urgently required to replace chemical pesticides (Duke *et al*., 2003).

1.3 Justification

Damage to grains by *S. zeamais* is serious for small-scale farmers who produce and after harvesting keep their grains under conditions which favour insect pest colonization (Abebe *et al*., 2009; Dobie *et al*., 1984). There is therefore the need for farmers to protect their grains from storage pests after harvesting. Maize improvement programmes therefore have focused on developing insect resistant varieties. These programmes are pursued through breeding in several national and international research institutes. However, earlier maize breeding programmes were more focused on improving yields at the expense of insect protection, resulting in the breeding of some varieties which were susceptible to storage insect pests attack (Mario *et al*., 2009). Also most past studies have focused on protecting the crops against pests in the field, with limited attention on protection in storage in Africa (Demissie *et al*., 2009; Getahun and Jembere, 2006; Getu, 2005; 2002; Getu *et al*., 2002; 2003; Tefera, 2004).

Recently, more attention has been paid to the protection of the crop in storage and there has been an increase in the intensity of the search for efficient, environmentally sound and safe control methods. One alternative to the use of chemical pesticides for control of stored product insect pests is the use of resistant varieties (Suleiman *et al*., 2015). The use of host plant resistance in Integrated Pest Management (IPM) of *S. zeamais*, particularly in tropical environment, where smallholder farmers produce and keep their harvested grains under conditions that favour insect pest colonization cannot be overemphasized. The use of host plant resistance as management option against insect pests of stored products has several benefits compared to the use of synthetic chemicals which have long-term environmental consequences. Resistant varieties are economical, easy to handle and use, and safe. It is also effective in managing maize infestation in storage (Muzemu *et al*., 2013). The use of host plant resistance is particularly important in Africa where farmers can hardly have enough money to purchase insecticides for protection of the crop in storage (Issa *et al*., 2011a; Keba and Sori, 2013).

Host plant resistance as an effective management strategy for postharvest insect pests associated with stored maize requires a better understanding of the susceptibility levels of different maize seed varieties to attack by these pests. Previous studies indicate that there exists variability in the genetic makeup of maize varieties for resistance to the maize weevil (Abebe *et al*., 2009; Dobie, 1974; Issa *et al*., 2011a; Kasozi *et al*., 2016; Mwololo *et al*., 2012). It is also known that different varieties of grains differ in their susceptibility to insect pest attack (Ajayi and Soyelu, 2013; Keba and Sori, 2013; Nwosu *et al*., 2015).

A total of thirty six (36) maize varieties had been released and registered in Ghana from 1983 to 2015 by Crops Research Institute (CRI) and Savanna Agricultural Research Institute (SARI) of the Council for Scientific and Industrial Research (CSIR) in Ghana in collaboration with International Institute of Tropical Agriculture (IITA) and International Maize and Wheat Improvement Centre (CIMMYT). There is scanty information on these varieties with respect to postharvest insect pests attack. Also, West Africa Centre for Crop Improvement, University of Ghana, maize breeding program has produced a number of high yielding hybrids that are yet to be released. Further, these hybrid varieties are yet to be tested for postharvest insect pest susceptibility. This study was undertaken to assess the response of some selected maize seed varieties from the maize breeding programme of three institutes in Ghana (Crops Research Institute [CRI], Savanna Agricultural Research Institute [SARI] and West Africa Centre for Crop Improvement [WACCI]) to attack by the maize weevil, *S. zeamais*.

1.4 Objectives

The main objective of the study was to determine the relative susceptibility of eighteen maize seed varieties from CRI, SARI and WACCI to attack by the maize weevil, *S. zeamais*. The specific objectives of the study were to:

- ☐ Determine F_1 progeny production and population growth of *S. zeamais* on the eighteen maize varieties;
- ☐ Determine the median development period of *S. zeamais* and susceptibility index of the eighteen maize varieties;
- ☐ Assess seed damage, seed weight loss and dust production due to *S. zeamais* infestation after storage period of three months;
- ☐ Determine the effect of *S. zeamais* infestation on viability of the eighteen maize seed varieties; and
- ☐ Determine the relationship among variables for susceptibility to *S. zeamais*.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Biology, Origin and Distribution of Maize

Maize is a member of the Poaceae (Gramineae) family that includes wheat, rice, oats, sorghum, barley and sugarcane. Maize is a diploid species that has 2n = 2x = 20 number of chromosomes (Baffour *et al*., 2014). Maize originated in central Mexico (Manandhar *et al*., 2001). The crop was introduced to Europe in the sixteenth century, from where it spread to Africa and Asia. It is now one of the most commonly grown crops around the world in both temperate and tropical regions. Maize seed comprises of the pericarp, endosperm and embryo (Figure 1). Based on the nature of the endosperm, composition of the kernel, colour of the kernel, where it is grown, maturity period and its usage, maize grains are subdivided into distinct types (Baffour *et al*., 2014). Kuleshov (1933) classified maize kernels into flint (*Z. mays indurata*), floury (*Z. mays amylacea*), dent (*Z. mays indentata*), popcorn (*Z. mays everta*), sweet (*Z. mays saccharata*) and starchy-sugary (*Z. mays amylea saccharata*) based on endosperm characteristics.

Maize was distributed throughout the world after European discovery of the Americans in the fifteenth century, mostly in the temperate regions (Farnham *et al*., 2003). Globally, North America (41%), followed by Asia (28%), Europe (10%), South America (10%) and Sub-Saharan Africa (6%) are the leading producers of maize (Food and Agriculture Organization Statistics [FAOSTAT], 2013). Maize was introduced into Africa in the sixteenth century and by the end of seventeenth century has become a major staple in West Africa (Nunn and Qian, 2010). It has replaced the local rice, *Oryza glabberima* due to its high yielding capabilities (Tweneboah, 2000). Major producing countries in Africa are South Africa, Nigeria, Ethiopia, Tanzania, Malawi, Kenya, Zambia, Uganda, Ghana, Mozambique, Cameroon, Mali, Burkina Faso, Benin, Democratic Republic of Congo, Angola, Zimbabwe, Togo, and Cote d'Ivoire (Food and Agriculture Organization Statistics [FAOSTAT], 2015).

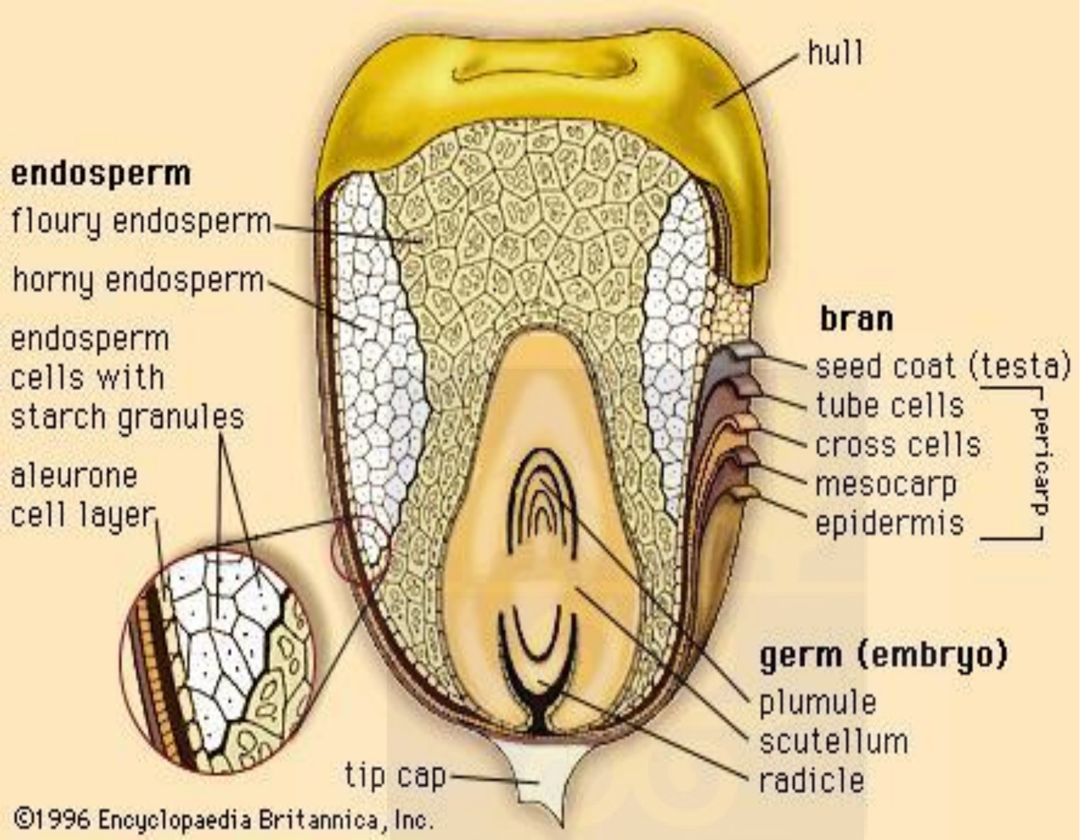


Figure 1: External and internal structure of a maize seed (Merriam-Webster Inc., 2006).

2.2 Utilization and Economic Importance of Maize

Maize occupies the third position next to rice and wheat in area of cultivation and total production (Food and Agriculture Organization Statistics [FAOSTAT], 2014). Besides being used as food and feed, maize serves as the main component for the manufacture of a lot of industrial products (Gupta *et al.*, 2015). Maize serves as good source of highly digestible carbohydrates and has higher protein and fat contents as compared to other cereals. It contains vitamin A, C, K and B-complex as well as large amount of beta-carotene and fair amount of selenium (Kumar and Jhariya, 2013).

Maize plays an essential role in the livelihood of smallholder farmers in sub-Saharan Africa. It is the largest staple crop in Ghana and contributes significantly to the diets of consumers. The grains can either be cooked, roasted, fried, ground, pounded or crushed to prepare different kinds of food items like tuozafi, kenkey, akple, banku, etc. (Morris *et al*., 1999). All these food types are readily available among different ethnic groups in various parts of Ghana. Apart from being used as food, maize is used in the preparation of animal diet due to its nutritional composition and health benefits. Maize can be used for the production of cereal baby foods, corn-oil, glucose, gum, starch and alcohol in processing industries. The starch obtained from maize can also be manufactured into valuable finished products. A watery by-product of maize called steep liquor is widely used as a medium for culturing microorganisms (Manueke *et al*., 2015). In the United States of America, approximately 40% (130 million tons) of the 332 million metric tons of maize grown annually is used for corn ethanol production (Torres *et al*., 2016).

2.3 Maize Breeding and Production in Ghana

Maize breeding in Ghana begun in the early 1930's after the crop was introduced by the Portuguese in the 16th century. The mandate of maize breeders in Ghana has mainly been to develop high yielding and stable maize varieties that will perform well in all the agro-ecological zones in Ghana (Ghana Grains Development Project [GGDP], 1986). Germplasms used by breeders in maize improvement programs in Ghana are sourced from the International Maize and Wheat Improvement Center (CIMMYT) in Mexico and International Institute of Tropical Agriculture (IITA) in Nigeria. Improved maize varieties developed by breeders and produced in Ghana include both open-pollinated varieties (OPV's) and hybrids. A total of 36 maize varieties (Table 1) were released and registered in Ghana from 1983 to 2015 in close collaboration between CRI and SARI of CSIR in Ghana with IITA and CIMMYT (Drought Tolerance Maize for Africa [DTMA], 2013; Ministry of Food and Agriculture [MoFA], 2015; Ministry of Food and Agriculture/Crops Research Institute/Savanna Agricultural Research Institute [MoFA/CRI/SARI], 2005). Maize is produced in all the ecological zones including the Forest, Coastal Savanna, Forest Savanna transition, Guinea Savanna, Sudan Savanna and Sahel Savanna of Ghana (Figure 2). Nevertheless, the leading producing areas are mainly in the Brong Ahafo, Eastern and Ashanti regions where 84% of the maize is grown, with the remaining 16% being grown in the Northern, Upper East and Upper West regions (Statistical Research and Information Department of the Ministry of Food and Agriculture [SRID-MoFA], 2011).

Figure 2: The agro-ecological zones in Ghana (Food and Agriculture Organization [FAO], 2005).

Table 1: Maize varieties released and registered in Ghana.

Name of Variety	Year of Release	Origin/Source	Colour/Texture	Yield (MT/Ha)	Maturity (Days)
Golden Crystal	1972	CRI/CIMMYT	Yellow/Dent	4.6	110 – 120
Laposta	1972	CIMMYT	White/Dent	–	120
Aburotia	1983	CRI/CIMMYT	White/Dent	3.5	105 – 120
Dobidi	1984	CIMMYT	White/Dent	5.5	120
Kawanzie	1984	CIMMYT	White/Flint	4.6	90 – 95
Safita-2	1984	CIMMYT	White/Dent	3.5	90 – 95
Okomasa	1988	IITA/CIMMYT	White/Dent	5.5	120
Abeleehi	1990	IITA/CIMMYT	White/Dent	4.6	105 – 110
Dorke SR	1992	IITA/CIMMYT	White/Dent	3.8	95
Obaatanpa	1992	IITA/CIMMYT	White/Dent	4.6	105
Mamaba	1996	CIMMYT	White/Dent	6.5	105
Cida-ba	1997	CIMMYT	White/Dent	6.5	110
Dada-ba	1997	CIMMYT	White/Dent	6.5	110
Dodzi	1997	IITA	White/Dent	3.5	80 – 85
Aziga	2007	CIMMYT	Yellow/Dent	4.7	110
Akposoe	2007	IITA/CIMMYT	White/Flint	3.5	80 – 85
Golden Jubilee	2007	CIMMYT	Yellow/Dent	5.0	105 – 110
Aburohemaa	2010	IITA	White/Dent	5.0	90
Abontem	2010	IITA	Yellow/Flint	5.0	75 – 80
Omankwa	2010	IITA	White/Dent	4.7	90
Honampa	2012	IITA	White/Dent	5.2	105 – 110
Aseda	2012	IITA	White/Dent	6.7	105 – 115
Opeaburoo	2012	IITA	White/Dent	7.5	110 – 115
Tintim	2012	IITA	White/Dent	7.9	110 – 115
Nwanwa	2012	IITA	Yellow/Dent	7.9	110 – 115
Odomfo	2012	IITA	Yellow/Dent	6.5	110 – 115
Sanzal-Sima	2012	IITA	White/Flint-dent	5.4	110
Ewul-Boyu	2012	IITA	White/Flint-dent	5.6	110
Wang-Dataa	2012	IITA	White/Flint-dent	4.7	90
Bihilifa	2012	IITA	Yellow/Flint-	4.6	90
Tigli	2012	SARI	Yellow/Flint-	5.2	120
Sika Aburo	2015	South Africa	White/Flint-dent	6.7	105 – 115
Kunjor-Wari	2015	IITA	White/Flint-dent	6.9	110
Suhudoo	2015	IITA	White/Flint-dent	6.7	110
Warikama	2015	IITA	White/Flint-dent	5.8	90
Kpari-Faako	2015	IITA	White/Flint-dent	5.7	90

Source: DTMA, 2013; MoFA, 2015; MoFA/CRI/SARI, 2005.

2.4 Insect Pests Associated with Stored Maize

One of the main causes of the high storage losses in tropical environment is the high incidence of storage pests. Although maize is an essential source of food for humans, it is also an excellent source of food and an ideal site of breeding for postharvest pests. It has been globally reported that insect pests are responsible for the high losses of stored grains. Postharvest insect pests of economic importance to maize can be classified into two orders; Coleopterans and Lepidopterans. Several insect species of these orders attack crops in the field and during storage. For maize, the most important insect pests associated with storage in most African countries are shown in Table 2.

Table 2: Most important storage insect pests of maize in Africa.

Insect Species	Order	Family
Primary Pests		
Sitophilus zeamais (Motschulsky)	Coleoptera	Curculionidae
Prostephanus truncatus (Horn)	Coleoptera	Bostrichidae
Rhizopertha dominica (Fabricius)	Coleoptera	Bostrichidae
Secondary Pests		
Oryzaephilus spp.	Coleoptera	Silvanidae
Carpophilus spp.	Coleoptera	Nitidulidae
Cryptolestes ferrugineus (Stephens)	Coleoptera	Cucujidae

Source: Abebe *et al.*, 2009; Hodges, 2012; Phiri and Otieno, 2008; Tefera *et al.*, 2011a.

2.5 Description of the Maize Weevil

The maize weevil (*S. zeamais*) is a member of the Coleopteran order and Curculionidae family. It varies from dull reddish-brown to almost black with shiny and pitted punctures usually about 3 – 3.5 mm long. The thorax is densely pitted, legs are prominent, and the wings are well developed and can fly readily. *Sitophilus zeamais* usually have four pale reddish-brown or orange-brown oval markings on the elytra. The head of the adult is prolonged to form a long snout with chewing mouth parts at the end. The antennae have eight segments which are often carried in an extended position when the weevil is moving. The males have median lobe of aedeagus with two longitudinal grooves dorsally and the females with lateral lobes of the Y-shaped sclerite pointed. The larvae of maize weevils are white, fleshy and legless. The eggs, larvae and pupae stages of the maize weevil are all spent inside the kernel and are rarely seen. The adult weevils emerge by biting a circular hole through external layers of the kernel (Centre for Agriculture and Bioscience International [CABI], 2010).

2.6 Economic Importance of the Maize Weevil

Both adults and larvae of *S. zeamais* feed on internal layers of maize grains. An infestation of this pest can start in the field (prior to harvesting) but greatest damage takes place in storage. Postharvest damage caused by *S. zeamais* affects both quantity (nutrient loss) and quality factors, with significant economic losses (Bern *et al.*, 2013) to the farmer or decreased benefit to the end user. The main effect caused by *S. zeamais* infestation to stored grains is the damage through feeding activities of the adult weevils and the development of egg, larva and pupa stages within the grain (Longstaff, 1981). The direct damage caused by *S. zeamais* is that they may cause quantitative and qualitative losses and reduction in seed viability. The seed whose germ has been attacked will not germinate. This may decrease future maize production for small-scale farmers who plant stored grains as seeds.

The use of stored grains as seeds accounts for almost 80 percent of the seeds used by small-scale farmers (Louwaars and De Boef, 2012). *Sitophilus zeamais* feeds on separate grains leaving only the hulls. Infested grains show characteristic emergence holes for the adults on the outer layers of the grains. Heavily infested grains by this pest usually become heated at the surface, sometimes to such an extent that germination takes place. The immature life stages of the weevil are spent inside the kernel, and they are hardly seen outside of the kernel. Internal feeding by this pest reduces both the quality and quantity of the grains (Longstaff, 1981). The maize weevil causes hollowing of whole previously intact grains. Severe infestation and feeding by this pest reduces the quality of the grains leaving only the hulls along with powdery white frass. The metabolic activity of *S. zeamais* accelerates fungal infection and growth (Beti *et al*., 1995).

2.7 Biological Description and Ecology of Maize Weevils

The adults are long lived and each adult female may lay approximately 150 eggs in its lifetime, although 50% may be laid in the first 4 – 5 weeks. Adult females lay white and oval eggs inside the kernel by chewing a small hole into which each egg is deposited. The hole is then sealed with a gelatinous secretion ("egg plug") that gives protection to the egg. The eggs laid by the adult weevils have incubation period of about 6 days at 25°C (Howe, 1952). Adult females require temperatures between 15°C and 35°C (with an optimum temperature around 25°C) and at moisture contents above 10% during egg laying. Immediately after hatching, the larvae tunnel, feed and develop inside the grain. The larva uses a combination of secretions and frass to seal the end of the burrow forming a pupal cell at the end of the fourth instar. The larva goes through a pre-pupal form for a short period prior to changing into the pupa (Longstaff, 1981). Pupation occurs inside the grain. The newly developed adult chews a circular hole in the grain where it emerges. Total developmental periods required by the maize weevil range from about 35 days under ideal conditions to above 110 days in unfavourable conditions (Birch, 1944; Howe, 1952).

2.8 Geographical Distribution and Host Plants of Maize Weevils

Sitophilus zeamais is found in all warm and tropical parts of the world especially in locations where maize is grown. These pests are carried all over the world in grain shipments and can establish themselves wherever there is food and where grain moisture and temperature are favourable. It is one of the most common insect pests of stored maize in most African countries and occurs in all sub-regions. Host countries in Africa for *S. zeamais* are Algeria, Angola, Benin, Botswana, Cameroon, Cape Verde, Central African Republic, Congo, Côte d'Ivoire, Egypt, Ethiopia, Gambia, Ghana, Kenya, Lesotho, Liberia, Libya, Malawi, Morocco, Mozambique, Nigeria, Rwanda, Senegal, Somalia and South Africa (Ayuk-Takem *et al*., 1982; Champ and Dyte, 1976; Clement *et al*., 1988; Delobel, 1992; Mould, 1973; Mpuchane *et al*., 2000; Thind and Muggleton, 1981; Virmani, 1980; Weaver *et al*., 1991). The maize weevil can develop on a wide range of cereal crops. It commonly attacks standing crops, particularly, maize before harvest. In addition to maize as a favourite host, it attacks rice (*Oryza sativa*), cassava (*Manihot esculenta*), sorghum (*Sorghum bicolor*), wheat (*Triticum aestivum*) and dried stored products (Centre for Agriculture and Bioscience International [CABI], 2010).

2.9 Management Options for Maize Weevils

The management options employed in controlling storage insect pests of maize include cultural control and sanitary methods, modified/controlled atmosphere techniques, modification of the storage environment/temperature control, chemical control, irradiation by microwave and gamma radiation, biological control, the use of botanical insecticides and host plant resistance.

2.9.1 Cultural Control and Sanitary Methods

Cultural and sanitary control measures aim at preventing insect pest infestation by rendering the crop environment less favourable for the pest. This is achieved through the use of a variety of techniques, many of which are considered old and traditional but serve to reduce the chance of insect colonization. Cultural control should be considered as the first ditch defence around which to build other control options (Coaker, 1987). This is maintained through proper cleaning of storage structures, removal and burning of all debris and residues before storage, frequent inspection during the storage period and proper drying of the grain to safe moisture content. Stored grain insect infestations rarely begin in the field. Early harvesting of the maize when it reached maturity will help reduce the likelihoods of attack by the maize weevil and other storage pests. These are done in order to eradicate insect eggs, pupae, and dormant adults that remain and develop in the stored grain (Centre for Agriculture and Bioscience International [CABI], 2010).

2.9.2 Irradiation

Gamma irradiation can effectively eliminate insect pests of stored products. Irradiation of *S. zeamais* by microwave and gamma radiation has been studied. Mortality studies were carried out on samples of maize seeds infested with *S. zeamais* using an ionizing radiation. According to Enu and Enu (2014), a sterilizing dose of gamma radiation from Cobalt-60 was determined for adults of *S. zeamais* on maize seeds and a dose of 250 to 500 Gy killed all *S. zeamais*. Hassan *et al*. (2010) used a laboratory microwave operating at a frequency of 2.45 GHz to determine the mortality of maize weevil. It was observed that 50°C treatment for 3 and 5 minutes could control the maize weevil and longer exposure time lead to higher mortality among adult weevils.

2.9.3 Controlled Atmosphere Technique (CAT)/Modified Atmosphere (MA)

CAT is based on the creation of a low-oxygen system/content in a specially-built gastight treatment chamber. The products are placed in these treatment chambers, after which the level of oxygen and temperature is adjusted to the specific insect and product that needs to be treated. De Carli *et al*. (2010) studied the effect of MA packaging on the mortality of *Sitophilus* spp. in organic maize grains. The results indicated that atmospheres containing higher than 20% carbon dioxide and lower than 2% oxygen eliminated most adult insects after 5 days of exposure. Complete inhibition of the insects was achieved after 30 days of exposure in carbon dioxide atmospheres.

Yuya and Birhanu (2014) investigated the efficacy of MA by composting fresh cow dung, chopped fresh sugarcane and chopped dry maize stubble each wetted at 60% moisture content in simulated storage structures in the field. It was reported that the gas from biological digestion of fresh cow dung and chopped sugar cane could be used as control option for maize storage pest in airtight storages. Another form of CAT that can be applied for the protection of stored products is hermetic storage or airtight storage. Studies have been carried out on different forms of hermetic storage and their conditions have proven effective in the protection of stored products from insect pests (Anankware *et al*., 2013; 2012; Jonfia-Essien *et al*., 2010; Sanon *et al*., 2011; Williams *et al*., 2017; Yakubu *et al*., 2011).

2.9.4 Chemical Control

Chemical insecticides and gaseous fumigants are used for the protection of stored produce against insect pests (Obeng-Ofori, 2007; 2011). Chemical control agents such as the use of synthetic insecticides in the form of sprays, fumigants and dusts are used in several countries and play an important role in controlling postharvest insect pests. Most farmers use a mixture of pirimiphos-methyl (Actellic) and permethrin, which is commercially sold as Actellic Super for controlling insect pests of their stored produce (De Groote *et al*., 2013). Shelling the grains and storing them in polypropylene bags after proper application of Actellic Super can effectively avoid insect pest infestation for a few months of storage (De Groote *et al*., 2013; Kimenju and De Groote, 2010).

Another frequently chemical insecticide used in controlling pests of stored products is Sofagrain which is packed in small bags that are spread in the granary. It is effective for three months during which the grains should not be consumed. Sofagrain has the same active ingredient as Actellic Super Dust (Rochat and Guenat, 2013). Aluminum phosphide (e.g. Phostoxin and Gastoxin) is also used as a storage insecticide for treating grains and seeds against postharvest insect pests to keep them safe until they are needed (Adu *et al*., 2014).

This practice has been widely adopted by farmers in African countries. Irrespective of their effectiveness, ready availability, fast acting and high reliability, their widespread use lead to environmental hazards, development of resistance, bioaccumulation and adversely affect non-target organisms (Dhuyo and Ahmed, 2007). They are also expensive and farmers lack requisite skills to handle and use them (Rugumamu, 2011) and their residuals could cause considerable loss of seed viability (Mutungi *et al*., 2014).

2.9.5 Temperature Control

Temperature is an essential component of the environment and the rate of metabolism, growth, development, reproduction, general behaviour and distribution of insect pests are largely controlled by it. Temperature extremes can be used to kill insects or prevent their injury. The shelf life of agricultural commodities is prolonged by cold temperature storage as this hinders the development of insect pests. Heat treatments are occasionally used to kill the larvae of insect pests in certain types of produce. Li *et al*. (2015) reported that mortality of *S. zeamais* was influenced by a variety of different treatment conditions, including temperature-time combinations, controlled atmosphere environment and heating rates. The mortality of adult *S. zeamais* was significantly higher and slowest heating rate (0.1°C/min) achieved the highest mortality under controlled atmosphere treatment. Golić *et al*. (2011) indicated that short-term exposure of weevils from *Sitophilus* genus at temperature of 50°C adversely affects their survival and progeny production.

2.9.6 Biological Control

Biological control using natural enemies is another management option for maize weevils. Biological control means that useful organisms are used to control harmful organisms. Many insect species that occur in the ecosystem of stored products are potential biocontrol agents and have been studied in the protection of stored product from insect pests. There have been various studies on biological control agents for *S. zeamais*. *Sitophilus zeamais* is commonly parasitized by pteromalids (and occasionally other Hymenopterans). In the case of the maize weevil, common pteromalid parasites found in the tropics include *Anisopteromalus calandrae*, *Lariophagus distinguendus* and *Theocolax elegans*. These biological control agents should be introduced at an early stage in the storage period for effective control of *S. zeamais* (Centre for

Agriculture and Bioscience International [CABI], 2010). Murata *et al.* (2016) found that the release of the combination of *Amphibolus venator and T. elegans* offered potentially effective biological control of *S. zeamais* at an early stage of infestation in stored brown rice. Chaisaeng *et al*. (2010) reported that the pteromalid parasitoid, *A. calandrae*, would be an effective biological control agent if it is introduced in sufficient numbers at the beginning of the storage period so as to suppress the initial increase of maize weevil populations.

2.9.7 The Use of Botanical Insecticides

Plant derived insecticides, such as extracts, powders and oils have been assessed against *S. zeamais*. The plant derived products used as protectants for stored agricultural commodities are normally obtained from leaves, roots, flowers, fruits, seeds, bark and stems of plants (Dupriez and De Leener, 1989). These can be made into various forms such as admixtures, dusts, wettable powders, emulsifiable concentrates, repellants and anti-feedants, as well as plant oils and extracts. Plants or extracts from a considerable number of other plants have exhibited toxicity to *S. zeamais*. These include: sweet orange (Gebreegziabiher, 2017); *Azadirachta indica* (Erenso and Berhe, 2016); *Eucalyptus* (Mandudzi and Edziwa, 2016); *Tagetes minuta* (Yeshaneh, 2015); *Newbouldia laevis* (Ogungbite and Oyeniyi, 2014); cayenne pepper, sweet pepper and lon cayenne pepper (Oni, 2014); and *Piper guineense*, *Gnetum africanum* and *Curcuma longa* (Asawalam and Chukwuekezie, 2012).

Various indigenous botanical materials namely *Allium sativum* (garlic bulbs paste), *Carica papaya* (pawpaw seed powder), *Cymbopogon citrates* (lemon grass shoot powder), *Cymbopogon nardus* (citronella shoot powder) and *Piper nigrum* (black pepper seed powder) were also tested against the maize weevil. They were found to exhibit a very high degree of insecticidal and/or anti-feedant properties leading to high adult mortality (Issa *et al*., 2011b).

2.9.8 The Use of Resistant Varieties

The use of varietal resistance is an important preventive method of protecting grains in storage (Throne *et al*., 2000). Resistant varieties possess best storage qualities and therefore play a significant role in the management of storage pests by reducing populations of insect pests below economic injury levels. There are wide variations in the reaction of maize genotypes to *S. zeamais* (Wiseman *et al*., 1970). *Sitophilus zeamais* resistant varieties are available and are useful for reducing losses to this pest (Issa *et al*., 2011a; Keba and Sori, 2013; Suleiman *et al*., 2015). Vowotor *et al.* (1994) investigated the influence of maize variety and storage form on the development of *S. zeamais* and found that they had influence on the site of weevil emergence from the kernel.

2.10 Protection Mechanism of Host Plant Resistance (HPR) in Maize Grains

According to Beck (1965), HPR is defined as attribute of a plant species which enables it to reduce the possible utilization of the plant as a host by insect pests. HPR encapsulated in the seed is available to farmers which make sure that after acquiring the seed, farmers need not put in any more inputs for the control of postharvest pests of maize. Thus postharvest insect resistant maize varieties would reduce storage losses, eliminate the cost of buying insecticides and its related health risks and environmental hazards (Mugo *et al*., 2001). HPR to postharvest insect pests demonstrates itself as antibiosis, antixenosis and tolerance (Ordás *et al*., 2002; Tefera *et al*., 2011b). Antibiosis is the ability of the plant to affect the biology of the pest after colonizing and feeding on the plant. Antixenosis or nonpreference is where the plant is undesirable as a host and the postharvest pest looks for alternative hosts. Tolerance is a form of resistance in which the plant has the ability to withstand or recover from the pest damage.

Stored grain resistance is the ability of a certain crop variety to produce grains that maintain better quality than other cultivated varieties following long storage under similar insect populations (Mbata, 1987). Evaluation of resistance to stored grain insect pests focuses on measuring antixenosis. Modern research on crop resistance to postharvest insect pests has mainly focused on investigating the factors which confer resistance to these pests. Several factors play a role in the ability of crop varieties to resist infestation by postharvest insect pests in stored grains. The mechanism of resistance in maize to *S. zeamais* has been researched in association to secondary chemistry, biochemical and physical features of maize varieties.

Some of the physical barriers of resistance for a crop like maize include well-fitting set of sheating leaves and tight husks (Kim and Kossou, 2003; Kossou *et al*., 1993; Mwololo *et al*., 2013), limited oviposition sites and hardness of seeds (Akpodiete *et al*., 2015; Ashamo, 2001). These have been proven to affect the successful and rapid multiplication of storage insect pests particularly in cereals. The quantity and quality of nutritional constituents have been described to have influence on the fecundity of the females and the development period of the pre-imaginal instars and the rate of adult emergence (Dobie, 1986; Nwosu *et al*., 2015). The presence of certain compounds had been found to have antifeedant properties, growth and oviposition inhibitory effects against *S. zeamais* adults. In maize, lipids, protein and sugar content have been stated to be involved in conferring resistance to the maize weevil (Arnason, 1992; Garcia-Lara and Bergvinson, 2014; Nwosu, 2016).

2.11 Measurement of Weevil Resistance in Stored Maize Grains

Several approaches have been proposed and are available to measure the susceptibility or resistance of stored product to insect pests in the laboratory. These methods include oviposition rates (Russell and Rink, 1965) and the relative number of weevils which complete development and emerge as adults (McCain *et al*., 1964). Parameters such as percentage of adult mortality, total progeny, percentage mortality of progeny, weight of progeny weevil, percentage damaged kernels and grain weight loss were used to assess maize grain resistance to *S. zeamais* (Widstrom *et al*., 1972). These parameters have helped in identifying resistant varieties.

The degree of weight loss resulting from the feeding of insects has been found to be a measure of maize grain susceptibility or resistance to the maize weevil. Higher weight loss will occur in susceptible varieties than in resistant varieties (Siwale *et al*., 2007). Adult mortality gives an assessment of the maize weevil resistance as the number of adult insects alive and those that died are counted at about ten (10) days after introducing weevils by counting (Tefera *et al*., 2011b). However, weevil's adult mortality does not give a good indication in measuring susceptibility of varieties to postharvest insect pests. Abebe *et al*. (2009) and Dobie (1974) reported significant differences among varieties when tested against *S. zeamais*. However, there was no variation among varieties for mortality of *S. zeamais*. Abraham and Firdissa (1991) found out in a laboratory test that adult *S. zeamais* survived for more than ten days. This further indicates that the mortality of *S. zeamais* may not be a reliable indicator in measuring resistance to this pest. Nevertheless, low adult weevil mortality gives an indication of the likelihood of high number of eggs laid by surviving adult weevils resulting in increase in number of weevils which complete development and emerge as adults.

2.11.1 Susceptibility Indices

Susceptibility indices are used in measuring the susceptibility of maize varieties to *S. zeamais*. Two susceptibility indices have been developed and recommended by Dobie (1974) and Urrelo (1990) which when compared have been found to give similar assessments of maize susceptibility to *S. zeamais* (Gudrups *et al*., 2001). These are the Dobie's susceptibility index and Urrelo's susceptibility index. Dobie's index of susceptibility assumes susceptible varieties would have more F_1 progeny as well as a shorter developmental period of the insect pest. Urrelo's index of susceptibility assumes that the more the number of egg plugs on the grain and the shorter the duration of first emergence of F_1 progeny, the more susceptible the variety. In both methods, a higher index score indicates greater susceptibility of the varieties.

Dobie's IS is calculated by transforming the number of F_1 progeny emerged from the grain into natural logarithms and dividing by the average developmental period, which is estimated from the middle point of the oviposition period to the emergence of 50% of the F_1 generation. The index is given by the formula: $\mathrm{IS} = \frac{\mathrm{Ln}\sum \mathrm{X}}{\mathrm{MDP}} \times 100$, where IS is Dobie's index of susceptibility, $\mathrm{Ln}\sum \mathrm{X}$ is the natural logarithm of the sum of the number of F_1 progeny emerged and MDP is the median development period (in days). Dobie's method is preferred to that of Urrelo's because it requires relatively short time for susceptibility assessment (Derera *et al*., 2001; Dhliwayo and Pixley, 2003; Dobie, 1974; Gudrups *et al*., 2001). Urrelo's index is calculated by transforming the number of egg plugs on the grain into natural logarithms and dividing by the date of first emergence of the F_1 generation. The index is given by the formula: $\mathrm{IS} = \frac{\mathrm{Ln}\sum \mathrm{E}}{\mathrm{DFE}} \times 100$, where, IS is Urrelo's index of susceptibility, $\mathrm{Ln}\sum \mathrm{E}$ is the natural logarithm of the sum of the number of egg plugs on the grains and DFE is the date of first emergence of F_1 progeny (in days). Urrelo's method requires intensive labour, although it has the advantage of terminating the assessment when the first F_1 progeny emerges (Gudrups *et al*., 2001; Urrelo *et al*., 1990).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Experimental Site

The experiment was carried out in the Entomology Laboratory of the Department of Crop Science, University of Ghana, Legon.

3.2 Test Maize Varieties

A total of eighteen (18) maize varieties (Table 3) were collected from the maize breeding programme of three institutes in Ghana (CRI in Kumasi, SARI in Tamale and WACCI, University of Ghana, Legon) and used for the experiment.

Table 3: Maize varieties used for the experiment.

Test Maize Varieties	Varietal Type	Source
Abontem	OPV	CRI
Aburohemaa	OPV	CRI
Obaatanpa	OPV	CRI
Omankwa	OPV	CRI
Aseda	Hybrid	CRI
Tintim	Hybrid	CRI
Ewul-Boyu	OPV	SARI
Kpari-Faako	OPV	SARI
Sanzal-Sima	OPV	SARI
Bihilifa	OPV	SARI
TZE-I 17	OPV	SARI
TZE-Y POP STR	Hybrid	SARI
Wang-Dataa	OPV	SARI
WACCI-M-1205	Hybrid	WACCI
WACCI-M-1215	Hybrid	WACCI
WACCI-M-1508	Hybrid	WACCI
WACCI-M-1510	Hybrid	WACCI
WACCI-M-1594	Hybrid	WACCI

OPV = Open-Pollinated Variety; CRI = Crops Research Institute; SARI = Savanna Agricultural Research Institute; and WACCI = West Africa Centre for Crop Improvement.

3.3 Weevil Culture

The initial stock culture used for the experiment was obtained from infested maize stored at the Entomology Laboratory of the Department of Crop Science, University of Ghana. The weevils were retrieved from the infested maize through sieving. Obaatanpa, a variety widely adopted by Ghanaian farmers was used to set up the stock insect culture. The grains were first sieved to get rid of dirt and broken particles and sterilized in an oven at 60°C for 3 hours to kill any insect eggs which might have been present in the grains. Glass jars used were also sterilized by heating at 60°C for 3 hours. Two hundred 200 adult weevils were introduced into 3 L glass jars with 1.2 kg of Obaatanpa replicated five times. This was followed by covering the glass jars with muslin cloth to prevent possible re-infestation. The jars were placed on inverted petri dishes in industrial oil on shallow trays to keep out other unwanted insects (Plate 1). The insects were allowed to oviposit for ten (10) days in the laboratory after which they were retrieved by sieving.

After 35 days from the mid-point of the oviposition period, the F_1 progeny was collected by sieving. The F_1 adult weevils that had emerged, which were 0 – 1 week old, were introduced into other glass jars seeded with maize for one week by which time they were 1 – 2 weeks old. Subsequent 0 – 1 week old adult weevils from the culture jars were transferred into other glass jars seeded with maize till they were 1 – 2 weeks old. This was repeated a number of times subsequently to obtain sufficient laboratory-reared insects of 1 – 2 weeks old for the experiments. This was done because the fecundity rate of weevils was found to increase from week one reaching a peak by week three and thereafter declines (Dobie, 1974).

Plate 1: Prepared weevil cultures that provided *S. zeamais* for the experiments.

3.4 Experimental Procedure and Design

The different varieties of maize seeds received were cleaned and kept in a cold room at 4°C for 1 week to kill any existing/hidden storage insect pests. The seeds were further air-dried in an oven at 60°C for 3 hours to a moisture content level of 12 ± 2%. This was followed by keeping the seeds for 1 week under the experimental conditions in an incubator for acclimatization.

One hundred and fifty (150) grammes of seeds from each maize variety were placed in a 250 mL glass jar. Thirty (30) unsexed adult weevils aged between 1 – 2 weeks from a culture maintained in the laboratory as described above were put into each glass jar to infest the 150 g seeds of each maize variety. This was followed by covering the glass jars with white muslin cloth to allow aeration and to prevent the weevils from escaping. After ten (10) days oviposition period, grain from each experimental jar was sieved to discard adult weevils which had laid eggs in the kernels. The experimental set up was maintained at 25 ± 2°C and 70 ± 5% RH and 12 h light: 12 h dark photoperiod in Rubarth Apparate GmbH RUMED laboratory test chamber (Plate 2). The experiment was laid out in a Completely Randomized Design (CRD), with eighteen (18) maize varieties replicated three (3) times. The set ups were kept in the laboratory under the same experimental conditions for 30 days to monitor and assess the emergence of F_1 progeny every day.

Plate 2: Experimental set up of 18 maize varieties in Rubarth Apparate GmbH RUMED test chamber.

3.5 Data Collection

3.5.1 Moisture Content

Moisture content of the eighteen (18) maize varieties was determined prior to introduction of the weevils. The moisture content of the maize varieties was measured by a moisture meter (Seedburo 1200D Digital Moisture Tester).

3.5.2 Adult Mortality

Assessment of adult weevil mortality was done 10 days after the introduction of the weevils. The seed lot was sieved and the number of dead and live weevils counted from each glass jar to obtain adult weevil mortality. The percentage adult weevil mortality was calculated by using the formula: Adult weevil mortality (%) = $\frac{\text{Number of dead weevils}}{\text{Total number of all weevils}} \times 100$.

3.5.3 F_1 Progeny Production

The entire set up was left without disturbance, until the first weevils which completed development and emerged as adults were seen. The jars were inspected every day to observe the emergence of F_1 adults. Daily counts and removal of the F_1 progeny were done to prevent the F_1 progeny from laying eggs in the maize samples to produce the F_2 generation. The observation and removal of F_1 progeny continued for 56 days by which time they were all expected to have emerged (Abebe *et al*., 2009).

3.5.4 Median Development Period (MDP)

The MDP was calculated as the time (in days) from the middle point of the oviposition period to the 50% emergence of the F_1 progeny (Dobie, 1977).

3.5.5 Seed Damage, Weight Loss and Weight of Seed Powder

Three months after introducing the weevils, 200 seeds were randomly selected from each glass jar to assess the number of damaged seeds (seeds with characteristic emergence holes) by weevil feeding. The content in each glass jar was separated into seeds, insects and dust using laboratory sieves to assess damaged and undamaged seeds from sampled seeds in each jar. Seed damage was calculated using the formula: Seed damage (%) = $\frac{\text{Number of damaged seeds}}{\text{Total number of seeds}} \times 100$.

Seed weight loss was determined using the count and weigh method expressed as: W (%) $= \frac{(Wu\times Nd)-(Wd\times Nu)}{Wu \times (Nd+Nu)} \times 100$; where, W = weight loss (%), Wu = weight of undamaged seed, Nu = number of undamaged seed, Wd = weight of damaged seed, and Nd = number of damaged seed (Gwinner *et al*., 1996). Seeds from each glass jar were sieved to collect the dust (frass) produced by the weevils. This was followed by weighing the dust with an electronic balance (KERN 870). This was done from the emergence of the first F_1 generation till the observation period of 56 days.

3.5.6 Index of Susceptibility (IS)

Dobie's IS was used to separate the maize seed varieties into various susceptible groups (Dobie, 1977). This involves the number of F_1 progeny and the length of median developmental time. The susceptibility index was determined at 56 days after infestation using the formula: $IS = \frac{Ln\sum X}{MDP} \times 100$; where, IS = index of susceptibility, $Ln\sum X$ = natural logarithm of the sum of the number of F_1 progeny emerged and MDP = median development period. Dobie's index was used to classify the 18 maize varieties into susceptible groups using a scale of ≤ 4 to ≥ 10 (Table 4).

Table 4: Dobie's scale of index.

Scale of Index	Interpretation
≤4	Resistant
4.1 – 6.0	Moderately resistant
6.1 – 8.0	Moderately susceptible
8.1 – 10	Susceptible
>10	Highly susceptible

3.5.7 Seed Germination Test

Seed germination test was conducted by randomly picking one hundred (100) seeds from each maize variety before and after the seeds were damaged by the weevils in each glass jar. The test was conducted under ambient laboratory conditions of 28 ± 1°C and 70 ± 5% RH with four (4) replicates of twenty five (25) seeds per replicate (each maize variety). The selected seeds were placed on a wetted filter paper in Petri dishes (Plate 3). The number of seedlings that emerged (normally germinated seeds) was counted and recorded at seven days after planting (DAP). The percentage germination (viability index) was calculated using the formula: $\text{GP}(\%) = \frac{\text{NSG}}{\text{TNS}} \times 100$; where, GP = germination percentage, NSG = number of seeds germinated from each Petri dish and TNS = total number of seeds tested in each Petri dish (Ogendo *et al.*, 2004).

Plate 3: Seed germination test of 18 maize varieties in Petri dishes.

3.6 Data Analysis

Data on adult mortality, seed damage and seed weight loss recorded in percentages were arcsine transformed whereas number of F_1 progeny was log transformed so as to stabilize the variance. Analysis of variance (ANOVA) for adult weevil mortality, number of weevils that completed development and emerged as adults, seed weight loss, seed damage and seed germination were conducted using GenStat statistical package 12th Edition. Mean separation was done by using Tukey standardized test to compare the significant differences between the treatments at 5% level of significance. Correlation analysis was used to determine the association among variables like moisture content, adult mortality, F_1 progeny, seed damage, weight loss, dust produced, germination percentage, median development period and susceptibility index.

CHAPTER FOUR

4.0 RESULTS

4.1 Seed Moisture Content of 18 Maize Varieties and Adult Mortality of *S. zeamais*

The varieties were highly significantly ($P<0.001$) different from each other for moisture contents (Table 5). Varieties such as Aburohemaa (13.1%), WACCI-M-1508 (13.2%), Omankwa (13.3%), WACCI-M-1594 (13.3%), WACCI-M-1215 (13.6%) and Abontem (13.8%) had relatively higher and significant moisture contents whereas Aseda (11.4%), TZE-I 17 (11.5%), TZE-Y POP STR (11.9%), Tintim (11.9%) and Bihilifa (11.9%) were found to contain significantly lower moisture contents.

Table 5: Moisture content of 18 maize varieties before *S. zeamais* infestation.

Varieties	Seed Moisture Content (%)
Aseda	11.4^{a}
TZE-I 17	11.5^{a}
TZE-Y POP STR	11.9^{ab}
Tintim	11.9^{ab}
Bihilifa	11.9^{ab}
Kpari-Faako	12.1^{abc}
Wang-Dataa	12.2^{abcd}
Ewul-Boyu	12.3^{abcd}
WACCI-M-1205	12.3^{abcd}
Sanzal-Sima	12.4^{abcd}
Obaatanpa	12.6^{abcd}
WACCI-M-1510	12.8^{abcd}
Aburohemaa	13.1^{bcd}
WACCI-M-1508	13.2^{bcd}
Omankwa	13.3^{bcd}
WACCI-M-1594	13.3^{bcd}
WACCI-M-1215	13.6^{cd}
Abontem	13.8^{d}
LSD ($P<0.05$)	0.86
CV (%)	4.2

Values followed by the same letter within the column are not significantly different at $P<0.05$.

There were highly significant (P<0.001) differences in *S. zeamais* mortality among the 18 maize varieties during the ten days of the oviposition period (Figure 3). Abontem (60.0%) had the highest weevil mortality rate followed by Aseda (59.8%), WACCI-M-1215 (53.3%), WACCI-M-1205 (24.4%) and WACCI-M-1508 (23.3%). *Sitophilus zeamais* fed with Aburohemaa recorded the lowest mortality (3.5%) followed by TZE-Y POP STR (2.2%), Kpari-Faako (4.4%), Obaatanpa (5.56%), Wang-Dataa (6.7%), Ewul-Boyu (7.8%), WACCI-M-1510 (7.8%) and TZE-I 17 (8.9%) after the 10 days of exposure. Number of dead weevils ranged from 12.2% to 17.8% in the other maize varieties.

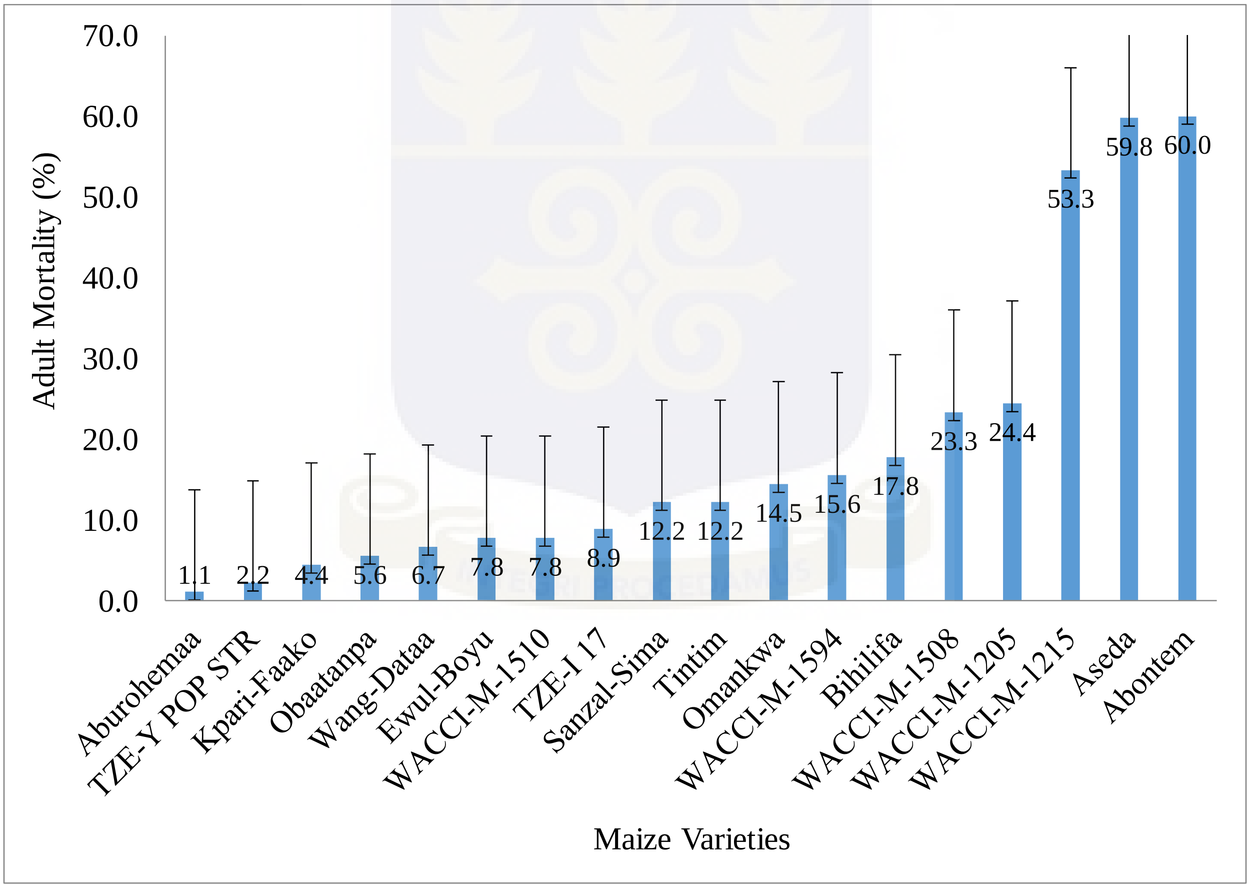


Figure 3: Adult mortality (%) of *S. zeamais* on 18 maize varieties after 10 days exposure.

4.2 F_1 Progeny Production and Population Growth of *S. zeamais* on 18 Maize Varieties

Highly significant ($P<0.001$) differences were observed at the time of first emergence of F_1 progeny of *S. zeamais* among the 18 maize varieties (Figure 4). The first batch of weevils completed development and emerged as adults at 27 days after set up (DAS) and were from Obaatanpa and Omankwa followed by Aburohemaa (28 DAS) and Abontem (29 DAS). However, the time of first emergence of F_1 progeny was 41 DAS in Aseda, and varied from 32 to 36 DAS among the remaining varieties.

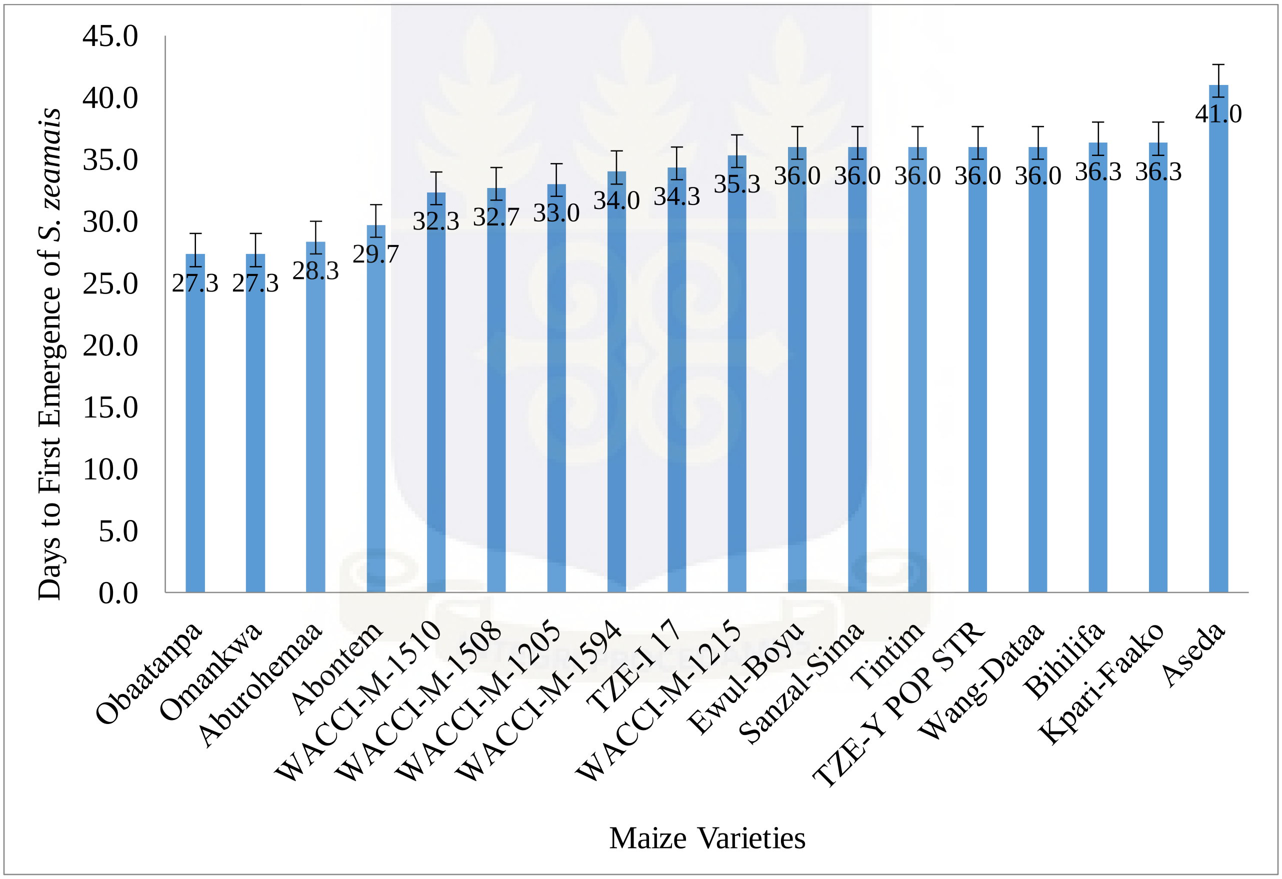


Figure 4: Days to first emergence of F_1 progeny of *S. zeamais* in 18 maize varieties.

There were variations and highly significant ($P<0.001$) differences observed among the 18 maize varieties in the number of weevils which completed development and emerged as adults during the assessment period (Figure 5). The highest number of F_1 progeny was observed in Aburohemaa (128.0) followed by Obaatanpa (105.3) and Omankwa (93.7). TZE-Y POP STR (10.7) and Aseda (5.3) had the lowest number of F_1 progeny. Numbers of F_1 progeny ranged from 23.7 to 50.0 in the remaining varieties.

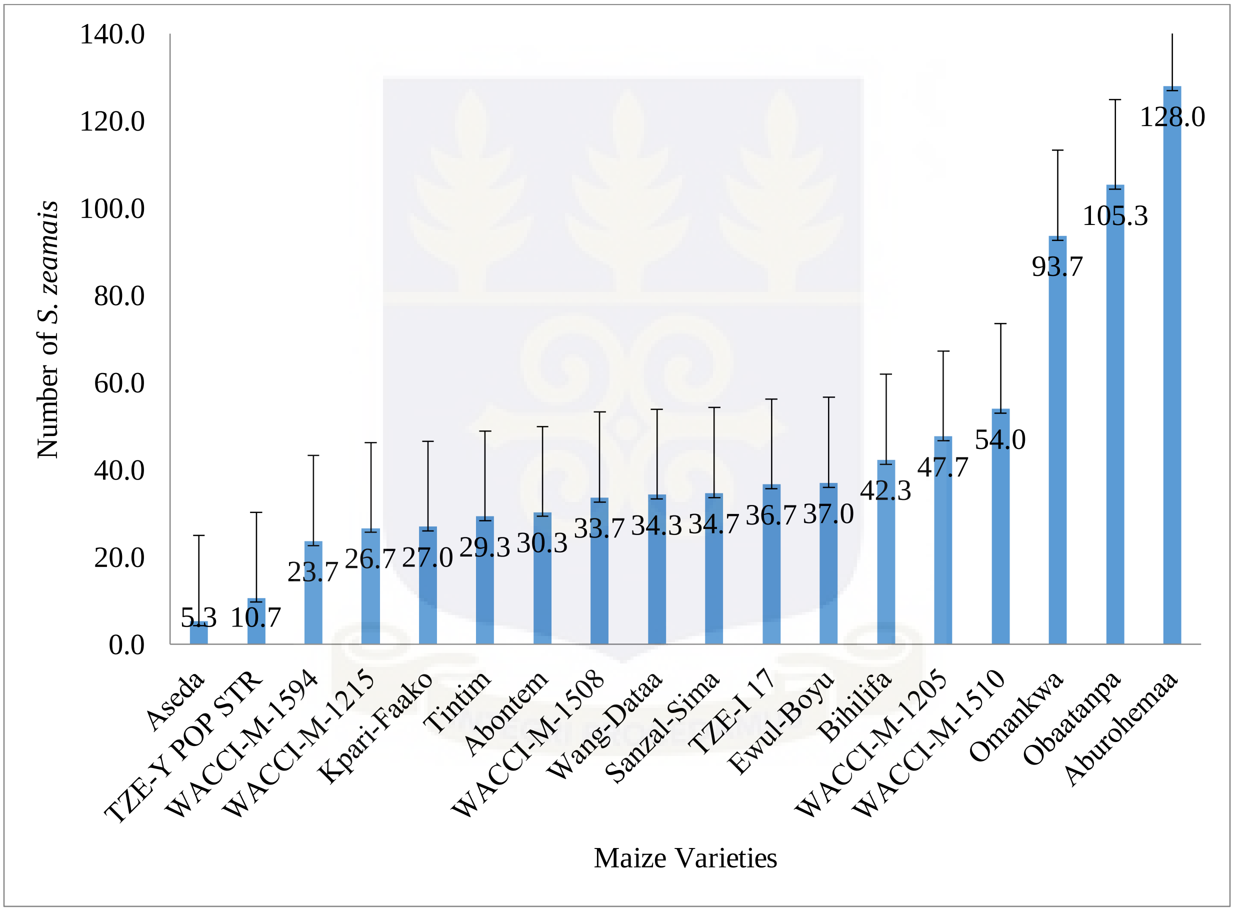


Figure 5: Total number of F_1 progeny of *S. zeamais* in 18 maize varieties from first emergence to the end of assessment period.

There were variations in the pattern of weekly emergence of *S. zeamais* among the 18 maize varieties. From Figure 6, it is clear that 26.5%, 37%, 20%, 9%, 4%, 2%, 1% and 0.5% of the F_1 progeny emerged in week 1, 2, 3, 4, 5, 6, 7 and 8, respectively. The highest number of F_1 progeny per week was observed in Aburohemaa, Obaatanpa and Omankwa whereas the lowest number was recorded in Aseda and TZE-Y POP STR. However, Ewul-Boyu, Kpari-Faako, Sanzal-Sima, Tintim, TZE-I 17 and TZE-Y POP STR varieties recorded a decline in the number of F_1 progeny after the first week. Generally, the number of F_1 progeny per week for most of the varieties was high in the first week with a peak in the second week for Aburohemaa, Obaatanpa, Omankwa, Abontem, WACCI-M-1205, WACCI-M-1215, WACCI-M-1508, WACCI-M-1594 and Wang-Dataa. Aburohemaa, Omankwa and Wang-Dataa produced F_1 progeny throughout the assessment period of eight weeks whereas Aseda, TZE-Y POP STR, Abontem and TZE-I 17 had no F_1 progeny emerging from the fifth week to the end of the assessment period. However, a general trend of decline in the number of F_1 progeny after the peaks week was observed in most of the varieties.

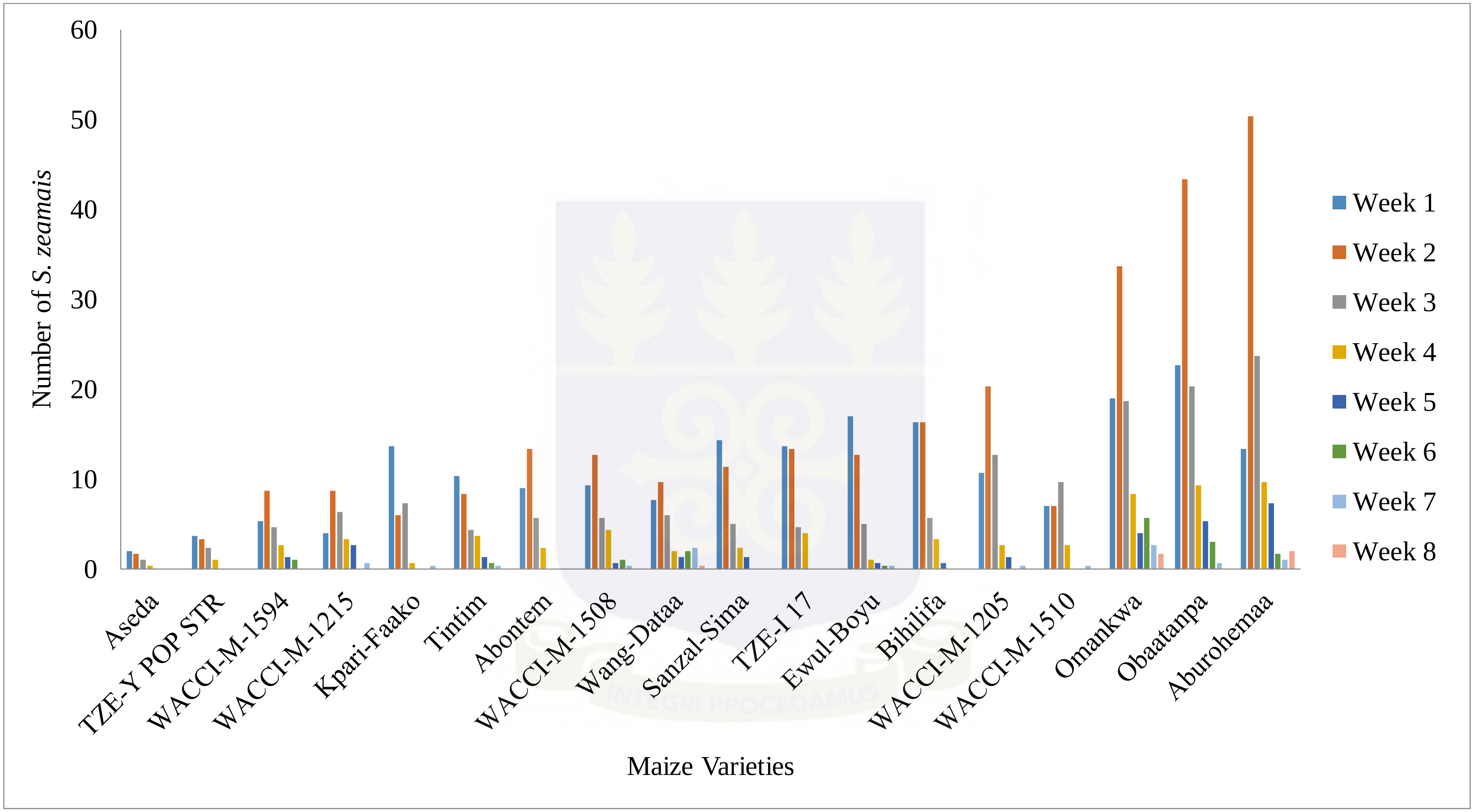


Figure 6: Trends on number of *S. zeamais* in 18 maize varieties from weeks 1 to 8.

4.3 Median Development Period (MDP) of *S. zeamais* and Index of Susceptibility (IS) of 18 Maize Varieties

Significant (P<0.010) differences were observed among the 18 maize varieties for the MDP (Figure 7). The MDP ranged from 37.7 days for Abontem to 47.3 days for Tintim. The majority of the F_1 progenies took 38.3 to 46.3 days to reach the 50% threshold from the middle point of oviposition in the other maize varieties.

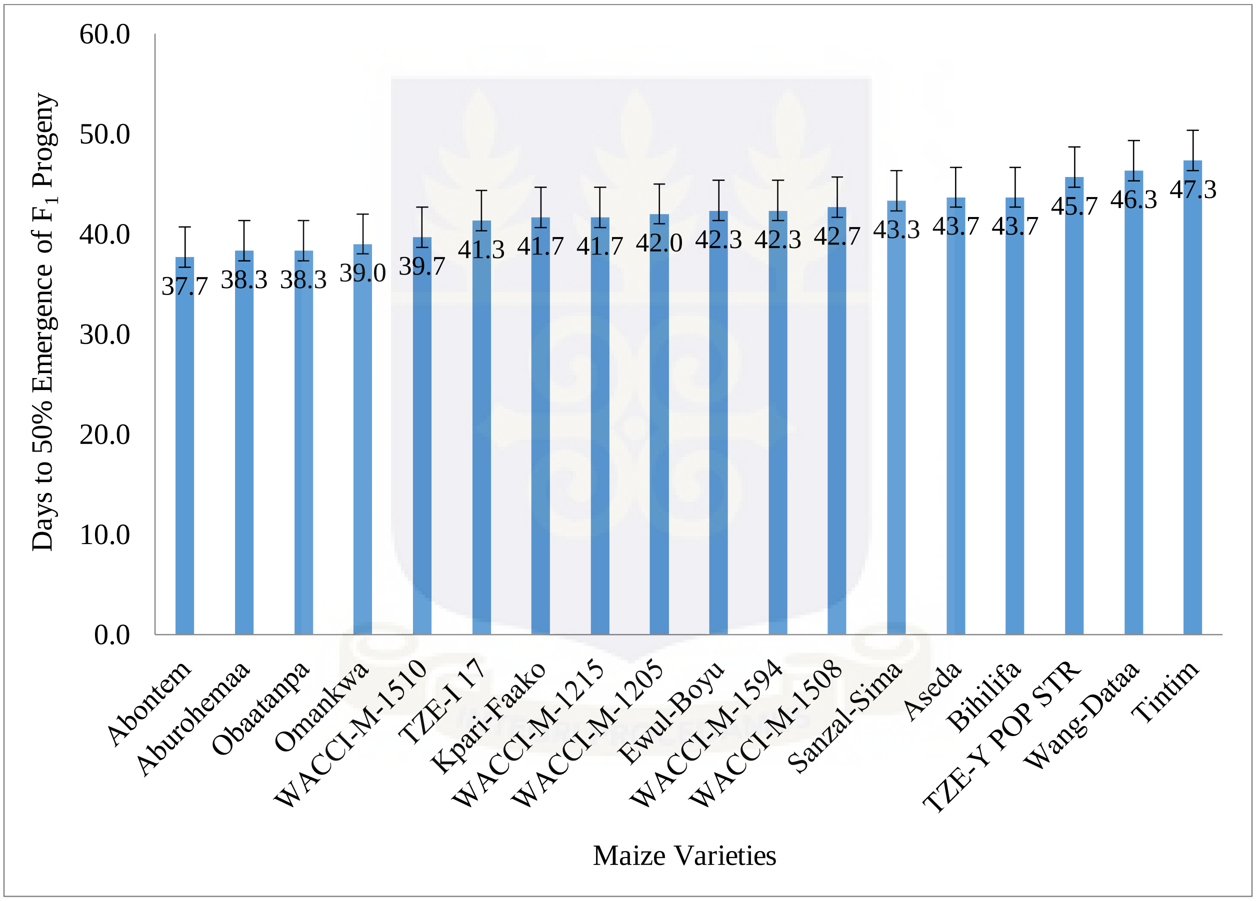


Figure 7: Median development time (in days) of *S. zeamais* in 18 maize varieties.

Significant (P<0.010) differences were observed in the IS among the 18 maize varieties. The IS ranged from 3.7 for Aseda to 12.6 for Aburohemaa (Figure 9). Using the Dobie's index of susceptibility score, Aseda had a value ≤ 4, TZE-Y POP STR fell within 4.1 – 6.0, Kpari-Faako, Tintim, WACCI-M-1215, WACCI-M-1594 and Wang-Dataa within 6.1 – 8.0, Abontem, Bihilifa, Ewul-Boyu, Sanzal-Sima, TZE-I 17, WACCI-M-1205, WACCI-M-1508 and WACCI-M-1510 had values within 8.1 – 10 and Aburohemaa, Obaatanpa and Omankwa were ≥ 10 (Figure 8).

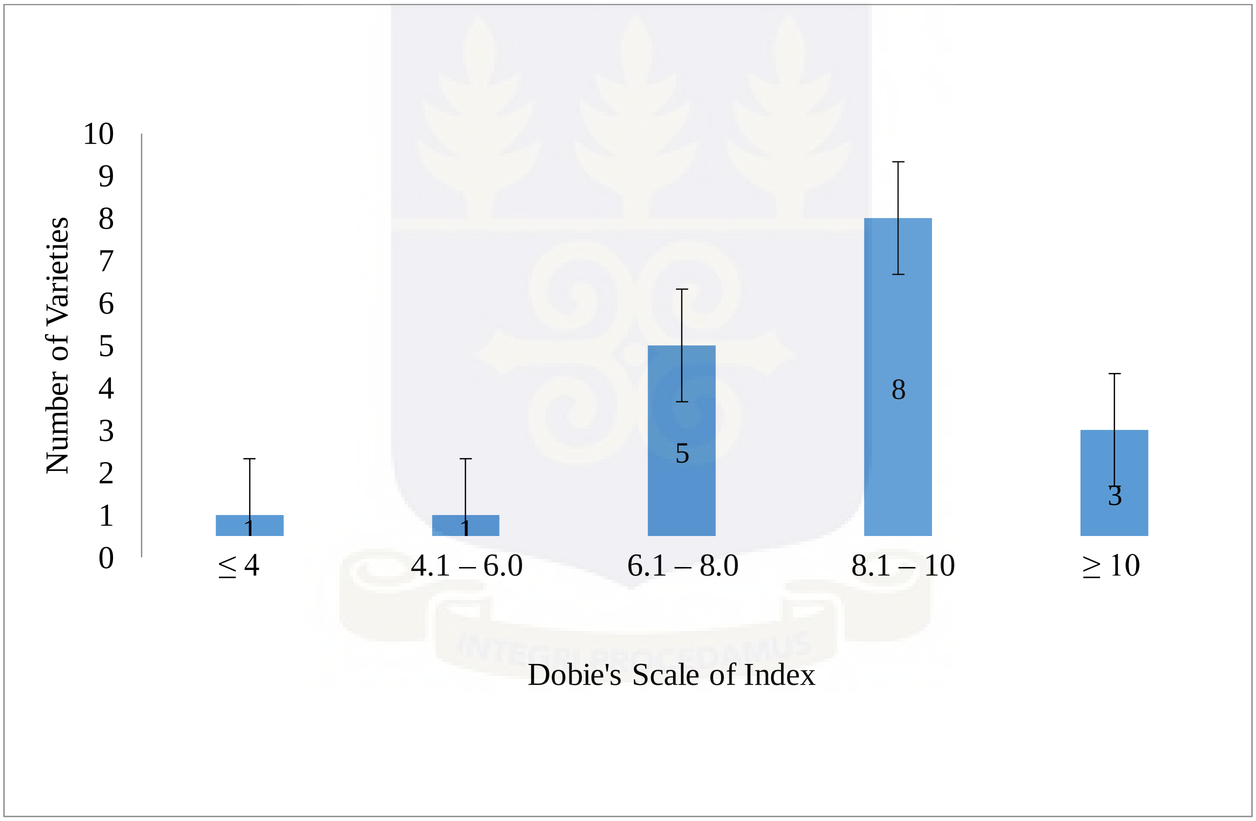
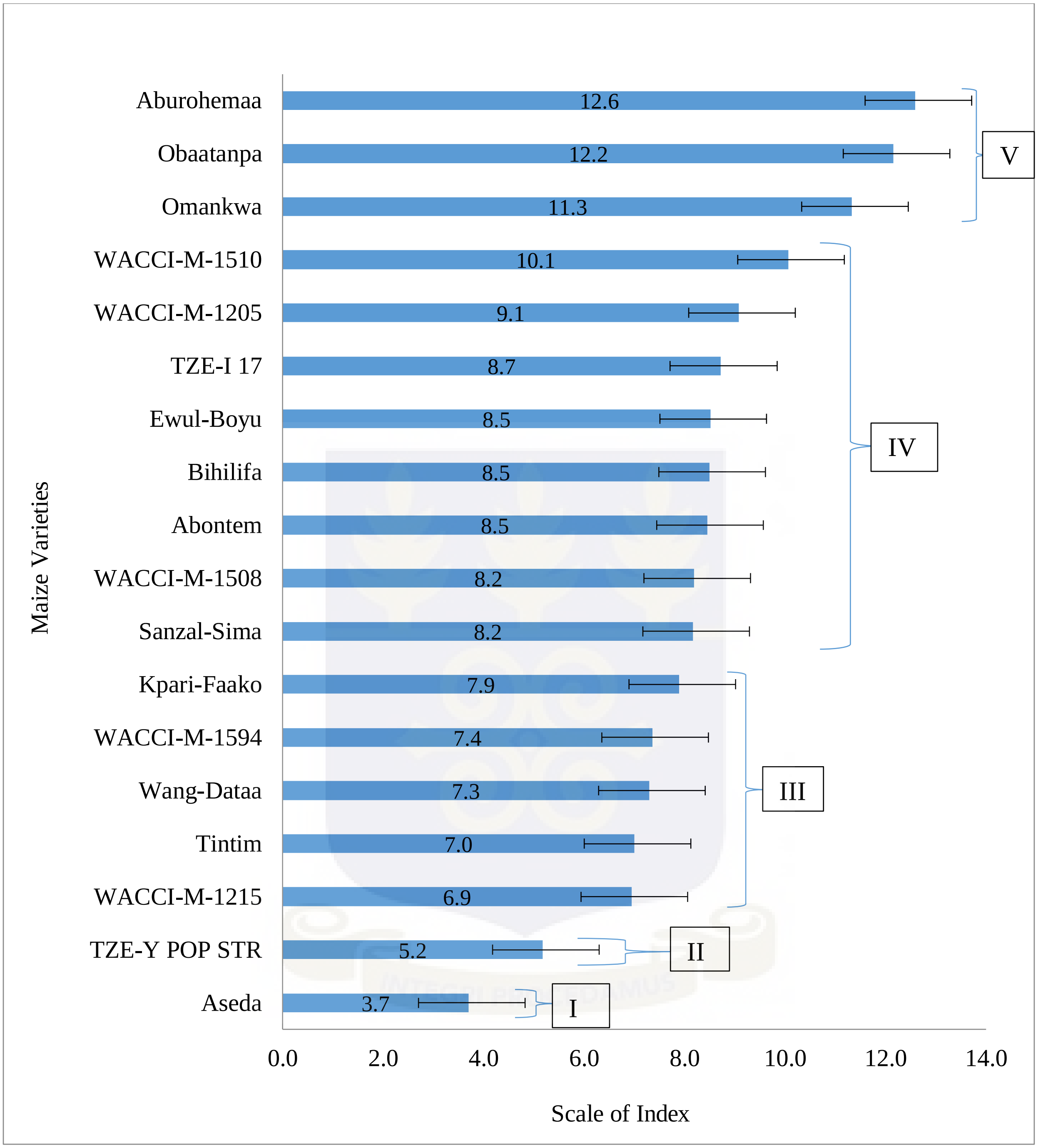


Figure 8: Frequency distribution of 18 maize varieties according to Dobie's scale of index.



I = Resistant, II = Moderately Resistant, III = Moderately Susceptible, IV = Susceptible and V = Highly Susceptible.

Figure 9: Susceptibility status of 18 maize varieties to *S. zeamais*.

4.4 Seed Damage Caused by *S. zeamais*

Highly significant ($P<0.001$) differences for percentage seed damage were observed among the 18 maize varieties after F_1 progeny emergence (Table 6). The variety with the most seed damage was Aburohemaa (26.0%), followed by Omankwa (23.8%) and Obaatanpa (20.8%). Percentage seed damage for Aseda (1.5%) was significantly lower than the remaining varieties.

4.5 Seed Weight Loss Caused by *S. zeamais*

Significant ($P<0.026$) differences were observed among the 18 maize varieties for seed weight loss. Percentage seed weight loss among the varieties ranged from 0.1% in Aseda to 2.4% in Obaatanpa after storage period of three months (Table 6). Percentage seed weight loss recorded in the remaining maize varieties varied from 0.7% to 2.3%.

4.6 Weight of Frass/Seed Powder Production by *S. zeamais*

The weight of powder produced from the 18 maize varieties after exposure to *S. zeamais* infestation revealed highly significant ($P<0.001$) differences after the storage period. The highest weight of powder produced after three months period of storage was observed on Aburohemaa which was 138.5 mg whilst the lowest value recorded was 4.9 mg on Aseda (Table 6).

Table 6: Extent of damage, weight loss and powder produced for 18 maize varieties after exposure to *S. zeamais*.

Varieties	**Seed Damage (%)**	**Seed Weight Loss (%)**	**Powder Produced (mg)**
Abontem	10.7^{abc}	1.1^{a}	32.8^{ab}
Aburohemaa	26.0^{e}	2.3^{a}	138.5^{e}
Aseda	1.5^{a}	0.1^{a}	4.9^{a}
Bihilifa	11.3^{abcd}	2.0^{a}	46.0^{abc}
Ewul-Boyu	8.7^{abc}	1.8^{a}	39.8^{abc}
Kpari-Faako	8.2^{abc}	2.3^{a}	28.9^{ab}
Obaatanpa	20.8^{cde}	2.4^{a}	116.3^{de}
Omankwa	23.8^{de}	2.3^{a}	103.3^{cde}
Sanzal-Sima	13.0^{abcd}	2.0^{a}	37.4^{ab}
Tintim	9.5^{abc}	1.4^{a}	31.3^{ab}
TZE-I 17	11.7^{abcd}	2.1^{a}	72.7^{bcd}
TZE-Y POP STR	5.3^{ab}	1.1^{a}	10.9^{ab}
WACCI-M-1205	14.5^{bcde}	1.7^{a}	52.3^{abc}
WACCI-M-1215	9.0^{abc}	0.9^{a}	28.7^{ab}
WACCI-M-1508	9.0^{abc}	1.4^{a}	36.6^{ab}
WACCI-M-1510	15.0^{bcde}	1.4^{a}	59.1^{abcd}
WACCI-M-1594	6.8^{ab}	0.7^{a}	25.4^{ab}
Wang-Dataa	12.7^{abcd}	1.9^{a}	37.2^{ab}
LSD ($P<0.05$)	6.9	1.3	34.4
CV (%)	34.8	47.7	41.5

Values followed by the same letter within the column are not significantly different at $P<0.05$.

4.7 Seed Germination

There were significant (P<0.044) differences among the 18 maize varieties in percentage germination of undamaged seeds (before weevil infestation). Percentage seed germination of non-infested seeds ranged from 87.0% in Tintim and WACCI-M-1508 to 99.0% in Aseda and TZE-I 17 (Table 7; Plate 4). However, there were highly significant (P<0.001) differences among the 18 maize varieties after *S. zeamais* infestation. The percentage seed germination ranged from 52.0% in Omankwa to 98.0% in Aseda after *S. zeamais* infestation (Table 7; Plate 5). The least actual percentage germination loss which was 1.0% was observed in Aseda and TZE-Y POP STR whereas the highest which was 41.0% was observed in Omankwa (Figure 10).

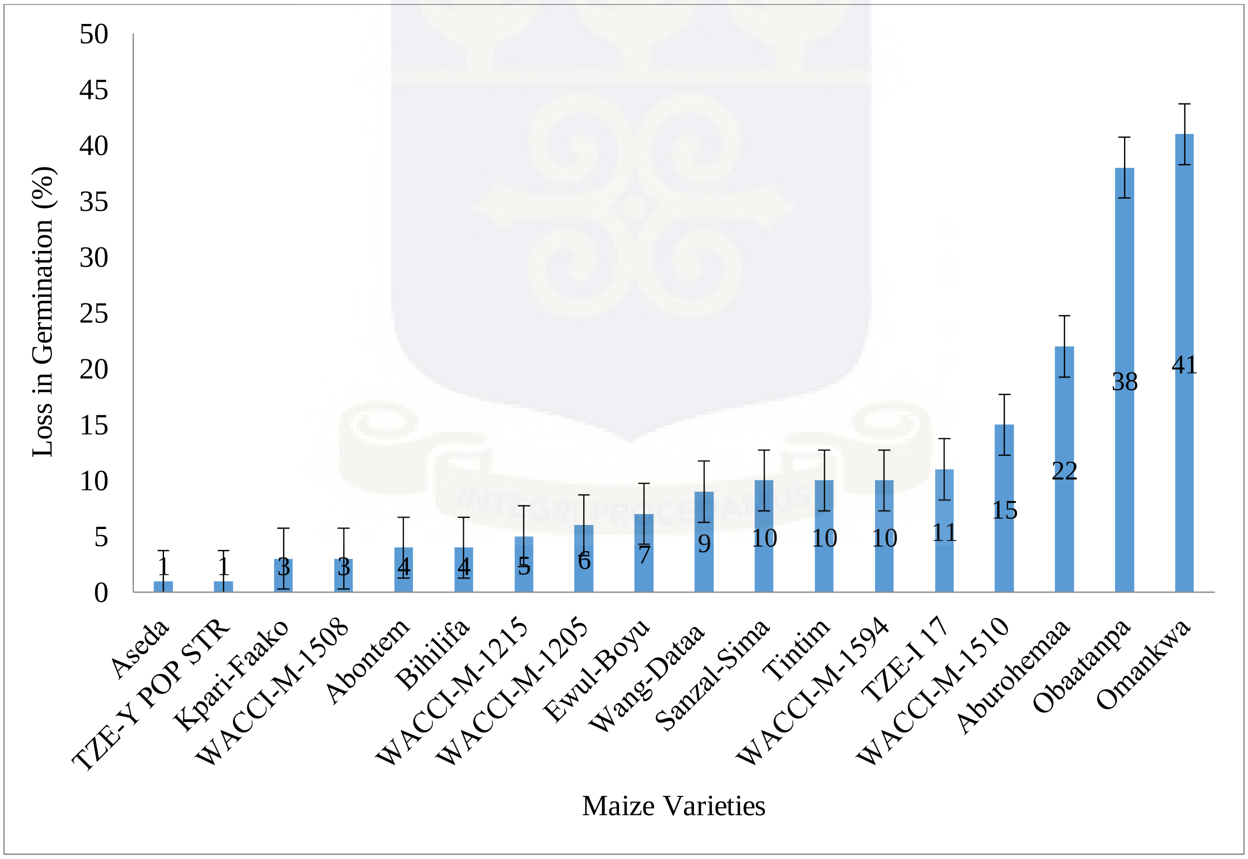


Figure 10: Actual loss in seed germination (%) after *S. zeamais* infestation in 18 maize varieties.

Table 7: Seed germination (%) of 18 maize varieties before and after exposure to *S. zeamais*.

Varieties	**Germination Percentage**	
	Before Weevil Infestation (%)	**After Weevil Infestation (%)**
Abontem	97.0^{ab}	93.0^{de}
Aburohemaa	91.0^{ab}	69.0^{bc}
Aseda	99.0^{ab}	98.0^{e}
Bihilifa	95.0^{ab}	91.0^{de}
Ewul-Boyu	95.0^{ab}	88.0^{de}
Kpari-Faako	95.0^{ab}	92.0^{de}
Obaatanpa	97.0^{ab}	59.0^{ab}
Omankwa	93.0^{ab}	52.00^{a}
Sanzal-Sima	97.0^{ab}	87.0^{de}
Tintim	87.0^{a}	77.0^{cd}
TZE-I 17	99.0^{ab}	88.0^{de}
TZE-Y POP STR	96.0^{ab}	95.0^{e}
WACCI-M-1205	93.0^{ab}	87.0^{de}
WACCI-M-1215	98.0^{ab}	93.0^{de}
WACCI-M-1508	87.0^{a}	90.0^{de}
WACCI-M-1510	97.0^{ab}	82.0cde
WACCI-M-1594	95.0^{ab}	85.0^{cde}
Wang-Dataa	91.0^{ab}	82.0^{cde}
LSD ($P<0.05$)	7.5	8.9
CV (%)	5.6	7.5

Values followed by the same letter within the column are not significantly different at $P<0.05$.

Plate 4: Maize seed germination before introducing *S. zeamais*.

Plate 5: Maize seed germination after exposure to *S. zeamais*.

4.8 Correlation Coefficient among Variables for Susceptibility to *S. zeamais*

Simple linear relationship among variables like moisture content, adult mortality, F_1 progeny, percentage seed damage, percentage seed weight loss, weight of dust produced, germination percentage, median development period and susceptibility index were determined and summarized (Table 8). It is clear from the correlation coefficient (r) that an inverse association existed between IS and adult mortality, MDP and percentage germination. However, the number of F_1 progeny, percentage seed damage, percentage seed weight loss, weight of dust produced and seed moisture content were positively correlated with the index of susceptibility. Percentage seed damage ($r = 0.9$, $P<0.001$), percentage weight loss ($r = 0.6$, $P<0.001$) and weight of seed powder ($r = 0.9$, $P<0.001$) showed positive and highly significant correlations with IS.

The MDP was negatively and highly significantly ($r = -0.3$, $P<0.001$) correlated with F_1 progeny emergence. Also, the MDP was insignificantly and negatively ($r = -0.2$, $P<0.235$) associated with adult mortality. Furthermore, the number of F_1 progeny showed highly significant and positive correlations between percentage seed damage ($r = 0.9$, $P<0.001$), percentage seed weight loss ($r = 0.6$, $P<0.001$) and weight of dust produced ($r = 0.9$, $P<0.001$) from the varieties. However, number of F_1 progeny was highly significant and negatively ($r = -0.7$, $P<0.001$) associated with percentage germination. Seed moisture content was positively ($r = 0.2$) correlated with F_1 progeny emergence and index of susceptibility ($r = 0.3$). But there was an inverse ($r = -0.5$) relationship between seed moisture content and median development period. Moreover, percentage seed damage was negatively and highly significantly ($r = -0.8$, $P<0.001$) correlated with percentage seed germination.

Table 8: Correlation analysis among variables for susceptibility to *S. zeamais*.

	IS	**Mor**	**F_1P**	**SMC**	**MDP**	**SD**	**SWL**	**Dust**	**SG**
IS	1								
Mor	-0.4**	1							
F_1P	0.9***	-0.4**	1						
SMC	0.3*	0.1	0.2	1					
MDP	-0.5***	-0.2	-0.3**	-0.5***	1				
SD	0.9***	-0.3**	0.9***	0.3	-0.3	1			
SWL	0.6***	-0.4***	0.6***	0.0	-0.1	0.6	1		
Dust	0.9***	-0.4**	0.9***	0.2	-0.4	0.9	0.6***	1	
SG	-0.7***	0.4**	-0.7***	-0.2	0.3	-0.8***	-0.5***	-0.7***	1

*, ** and *** designate significance at 0.05, 0.01, and 0.001 probability levels respectively.

IS = index of susceptibility, Mor = mortality, F_1P = F_1 progeny, SMC = seed moisture content, MDP = median development period, SD = seed damage, SWL = seed weight loss and SG = seed germination.

CHAPTER FIVE

5.0 DISCUSSION

5.1 Seed Moisture Content of 18 Maize Varieties and Adult Mortality of *S. zeamais*

More weevils completed development and emerged as adults in maize varieties with higher moisture content which suggests that seed moisture content plays a significant role in susceptibility of maize to insect pests attack. This confirms the observations by Ajayi and Soyelu (2013) and Keba and Sori (2013) who reported that more weevils developed in maize varieties with higher moisture content. Birch (1944) also reported that the oviposition rates of *S. zeamais* are influenced by both temperature and grain moisture content. The lower moisture content in Aseda and TZE-Y POP STR might have discouraged *S. zeamais* from colonizing, feeding and oviposition. This could account for the low number of weevils which completed development and emerged as adults from these varieties. However, maize weevils which completed development and emerged as adults were high in TZE-I 17, Tintim and Bihilifa despite their low moisture contents indicating that seed moisture content did not influence *S. zeamais* on these varieties.

Seed moisture content was positively correlated with F_1 progeny emergence and index of susceptibility but had an inverse relationship with median development period. This suggests that under normal conditions, *S. zeamais* will prefer maize varieties with higher moisture content and will only attack varieties with lower moisture content under conditions where their preferred variety is not available. There is therefore the need for farmers who store maize seeds for future use to dry their seeds to safe moisture contents and ensure that an equilibrium relative humidity is maintained throughout the storage period.

The high weevil mortality rate for Abontem, Aseda, WACCI-M-1508, WACCI-M-1205 and WACCI-M-1215 might be due to certain chemical compounds in them that hinder the development of this pest. The other maize varieties namely Aburohemaa, TZE-Y POP STR, Kpari-Faako, Obaatanpa, Wang-Dataa, Ewul-Boyu, WACCI-M-1510, TZE-I 17, Sanzal-Sima, Tintim and Omankwa recorded the least percentage of adult weevil mortality. These maize varieties provided a more favourable environment for egg laying, egg hatching and development of this pest.

Maize weevils which completed development and emerged as adults were, however, high in Abontem, WACCI-M-1215, WACCI-M-1205 and WACCI-M-1508 despite their high mortality rates indicating that adult mortality rate does not contribute significantly to maize resistance to *S. zeamais*. Abebe *et al*. (2009) and Dobie (1974) reported significant differences among varieties when tested against *S. zeamais*. However, there was no variation among varieties for mortality of *S. zeamais*. Abraham and Firdissa (1991) found out in a laboratory test that adult *S. zeamais* survived for more than ten days. These indicate that adult weevil mortality is not a good indicator for measuring resistance. Nevertheless, low adult weevil mortality gives an indication of the likelihood of high number of eggs laid by surviving adult weevils resulting in increase in number of weevils which complete development and emerge as adults.

5.2 F_1 Progeny Production and Population Growth of *S. zeamais* on 18 Maize Varieties

The variations observed in the number of weevils which completed development and emerged as adults indicate that maize weevil's development is affected by the maize varieties. It also revealed that there existed variation in susceptibility to *S. zeamais* attack among the varieties. Dobie (1986) and Nwosu *et al.* (2015) reported that the quantity and quality of nutrient constituents had influence on the fecundity of the females and weevils which complete development and emerge as adults. Thus, weevil development and emergence is faster on a more susceptible host. Number of weevils which completed development and emerged as adults was highly associated with the susceptibility of the varieties to *S. zeamais* infestation. Consequently, susceptible varieties produced more number of F_1 progeny in a short period as compared to the resistant varieties. This could explain why the first batch of F_1 progeny emerged early in Obaatanpa, Omankwa and Aburohemaa and consequently higher number of F_1 progeny during the first two weeks.

Higher numbers in such varieties might also be attributed to the age group of adult *S. zeamais* used for the experiment. This is because earlier studies by Dobie (1974) indicated that the fecundity rate of weevils increase from week one reaching a peak at week three and thereafter decline. The low weevil emergence in Aseda and other maize varieties can be attributed to high mortality of the adult weevils. These adult weevils might have died after laying few eggs which resulted in few progeny. The low weevil emergence in other varieties like TZE-Y POP STR, Kpari-Faako, Tintim, WACCI-M-1215 and WACCI-M-1594 may possibly be attributed to absence of essential nutrients and unbalanced proportion of nutrients leading to the death of the larvae (Garcia-Lara *et al.*, 2004; Metcalf and Luckman, 1994). The significant variation for number of weevils which completed development and emerged as adults among the varieties could be due to antibiosis effects from the varieties leading to retarded development of weevils' progeny and sometimes death of weevils before laying eggs (Derera *et al*., 2001).

The study revealed that the period from week one to week three recorded higher number of F_1 progeny with a peak emergence in week two in the eighteen maize varieties. The population of *S. zeamais* was however, relatively low in the other periods of the week particularly after week five. The daily removal of the F_1 progeny could account for the general trend of decline in the number of F_1 progeny after the peaks week. This did not allow the F_1 progeny to lay eggs in the maize varieties to produce the F_2 generation. The significant variation in the developmental periods of *S. zeamais* among the varieties could have contributed to the variations in the weekly trends of *S. zeamais*.

The observed differences in the number of weevils which completed development and emerged as adults among the varieties for the different periods may be due to the variations in the hardness of the seeds and/or the quantity and quality of nutritional constituents present in the seeds. Dobie (1986) reported that quantity and quality of nutrient constituents had influence on the fecundity of the females and the development period of the pre-imaginal instars and the rate of adult emergence. Kim and Kossou (2003) and Mwololo *et al*. (2013) also stated that physical barriers such as hardness of seeds affected the successful and rapid multiplication of insect pests. Hence *S. zeamais* had enough resources for their multiplication and infliction of damage to varieties such as Aburohemaa, Obaatanpa and Omankwa. The observed differences could also be due to the high percentage of parental survival after the ten days of oviposition. Larger number of parental survival is an indication of the likelihood of more egg laying from the adult weevils resulting in more number of F_1 progeny.

The results of the correlation analysis also support the above statements, indicating that *S. zeamais* developed faster on varieties with higher index of susceptibility. This suggests that under normal conditions, *S. zeamais* will prefer highly susceptible varieties and will only attack less susceptible varieties under conditions where their preferred variety is not available. The implication of these results on the management of this pest in stored maize is that the adult emergence of the pest peaks at the first two weeks and thus high damage and weight loss would be inflicted to susceptible varieties. However, control strategies against *S. zeamais* should be intensified by farmers who store maize seeds for future use at the beginning of seed storage provided the seed is planned to be stored beyond three months. This will drastically reduce the population of this pest in stored maize, thus minimizing seed damage, seed weight loss and loss of viability of the seeds in the succeeding months.

5.3 Median Development Period (MDP) of *S. zeamais* and Index of Susceptibility (IS) of 18 Maize Varieties

The observed MDP of *S. zeamais* on the 18 maize varieties are within the range that has been reported by some authors. Howe (1952) reported that the total developmental periods of *S. zeamais* range from 35 days to 110 days depending on the conditions during storage. Vowotor *et al*. (1994) found that the development of the maize weevil ranged from 31.5 days to 52.0 days from egg hatch to adult emergence at 25^{o}C and 70 – 75% RH. The range of developmental period for *S. zeamais* in this study is also in conformity to the ranges observed by Keba and Sori (2013). The variations found in MDP indicate that the development of this pest is influenced by the maize variety on which it feeds. Both diet and varietal differences have been found to influence developmental time and reproductive ability of *Sitophilus* species in cereals (Ajayi and Soyelu, 2013; Athanassiou *et al.*, 2017; Goftishu and Belete, 2014; Keba and Sori, 2013;

Muzemu *et al*., 2013; Ojo and Omoloye, 2016; Sharma *et al*., 2016). Generally, as the MDP increases, the emergence of the F_1 progeny decreases.

In addition, the prolonged developmental time observed in the resistant and moderately resistant varieties contributed to the reduction in *S. zeamais* population. Abebe *et al*. (2009) stated that prolongation of developmental periods reduces the number of weevil generations. A longer median developmental period slowed down the developmental stages of *S. zeamais*. The shorter developmental period observed in the susceptible and highly susceptible varieties indicates that the number of *S. zeamais* multiplied more quickly than when it was longer. Dobie (1974) reported shorter developmental periods in susceptible maize varieties tested against *S. zeamais*. Therefore, Aburohemaa, Obaatanpa and Omankwa have been found to be suitable for the feeding and development of *S. zeamais*.

The results of the correlation analysis also indicate an inverse relationship existed between median development period and F_1 progeny emergence and the index of susceptibility. The outcome of this study showed a high degree of variation in the IS of the varieties with Aburohemaa which produced twenty four (24) times as many F_1 progeny as Aseda. This observation is not surprising since variation in median development time and F_1 progeny emergence were observed among the eighteen maize varieties. This outcome conforms to the outcome of the correlation analysis that an inverse relationship existed between the IS and adult mortality and MDP. On the other hand, the number of F_1 progeny and seed damage were positively correlated with the IS. This finding is in conformity to the assumption of Horber (1988) that the higher the number of F_1 progeny as well as the shorter the length of the developmental period, the more susceptible the varieties would be.

The study revealed that, only one variety (Aseda) was found to be resistant to *S. zeamais* based on Dobie's index of susceptibility. The study also found TZE-Y POP STR variety to be moderately resistant to *S. zeamais*. Furthermore, five varieties, namely Kpari-Faako, Tintim, WACCI-M-1215, WACCI-M-1594 and Wang-Dataa were regarded as moderately susceptible to *S. zeamais*. Abontem, Bihilifa, Ewul-Boyu, Sanzal-Sima, TZE-I 17, WACCI-M-1205, WACCI-M-1508 and WACCI-M-1510 maize varieties were classified as being susceptible to *S. zeamais*. The remaining three varieties, namely Aburohemaa, Obaatanpa and Omankwa were categorized as highly susceptible to *S. zeamais*.

5.4 Seed Damage Caused by *S. zeamais*

Sitophilus zeamais caused considerable damage to susceptible and highly susceptible varieties than moderately resistant and resistant varieties. Goftishu and Belete (2014) and Tefera *et al*. (2011a) observed that the degree of damage in storage is influenced by the number of weevils which complete development and emerge as adults for each generation period as well as the length of each life cycle and varieties allowing more rapid emergence of adults experience more damage. Feeding activity was most intense in highly susceptible and susceptible varieties resulting in high percentage seed damage. Generally, percentage seed damage increased with increasing number of weevils which completed development and emerged as adults during the assessment period. Consequently, seed of maize varieties with high number of weevils which completed development and emerged as adults showed the most damage. This observation is not surprising since variation in weevils which completed development and emerged as adults were observed among the eighteen maize varieties.

The results of this study showed that when *S. zeamais* is left uncontrolled on susceptible maize varieties for more than three months, the quality factors of the grains would be significantly reduced. This is because the percentage seed damage will be more than 50% (Keba and Sori, 2013). Less seed damage could be attributed to antixenosis mechanisms like a smooth pericarp which could deter *S. zeamais* from oviposition and feeding and also prevents mandibles from gripping maize kernels. This outcome was corroborated by the outcome of the correlation analysis performed on the susceptibility variables which indicated that the number of F_1 progeny had significant effect on seed damage. A strong positive relationship existed between F_1 progeny emergence and seed damage which confirmed that a large number of weevils that completed development and emerged as adults from the seed caused huge seed damage. Hence it was not surprising that Aburohemaa which produced the highest number of F_1 progeny recorded the highest percentage seed damage whereas Aseda produced the lowest number of F_1 progeny as well as least percentage seed damage.

5.5 Seed Weight Loss Caused by *S. zeamais*

The highest weight loss occurred in the highly susceptible varieties whereas the lowest occurred in the resistant varieties. However, there appeared to be exceptions to this pattern. Howe (1965) reported that the weight loss caused by storage insect pests is influenced by several factors including the insect species, environmental conditions, length of storage time and the product itself. This is not only true for *S. zeamais* in maize but for the lager grain borer, *Prostephanus truncatus* Horn in dried chips of plantain, cocoyam, cassava and yam (Isa *et al*., 2012), *Callosobruchus maculatus* (Fab.) in cowpea (Audi *et al*., 2011), *C. maculatus* in Bambara groundnut (Dauda *et al*., 2009) and *P. truncatus* and *Araecerus fasciculatus* Degeer in dried yam chips (Danjuma *et al*., 2008).

The percentage weight loss in this study might have been higher than those obtained if the F_1 progenies had been allowed to lay eggs in the maize varieties to produce F_2 generation and other subsequent generations. This could have resulted in increase in the number of progenies, number of damaged seeds and consequently higher weight loss in the maize varieties. The percentage seed weight loss by *S. zeamais* infestation was corroborated by the outcome of the correlation analysis. It indicated that the number of F_1 progeny, MDP, index of susceptibility and seed damage had significant effect on seed weight loss. From the study it was realized that positive association existed between percentage seed weight loss and the number of F_1 progeny, index of susceptibility and seed damage. However, there was an inverse relationship between seed weight loss and median development period. From the correlation analysis, it was confirmed that a large number of weevils that completed development and emerged as adults from the seed caused huge seed damage resulting in high seed weight loss. This agrees with the findings of Keba and Sori (2013) and Mwololo *et al.* (2012).

5.6 Weight of Frass/Seed Powder Production by *S. zeamais*

Generally, maize varieties with higher number of F_1 progeny and higher IS recorded the highest weight of seed powder. Thus, varieties with lower number of F_1 progeny and lower IS recorded low weight of seed powder. The degree of infestation and feeding by this pest also determine the quantity of powder produced. Feeding activity by this pest was severe in highly susceptible and susceptible varieties resulting in the high weight of powder produced. There was significant and strong positive relationship between the quantity of seed powder or dust produced by *S. zeamais* and index of susceptibility, number of F_1 progeny produced and seed damage. The relationship between the number of F_1 progeny emergence with the increase in the quantity of seed powder has also been observed in many studies (Keba and Sori, 2013; Nwosu *et al.*, 2015; Suleiman *et al.*, 2015).

Weight of seed powder also followed similar trend as the percentage seed damage and susceptibility of the different maize varieties, though there appeared to be exceptions to this pattern. The variation in weight of seed powder may be caused by physical characteristics of the seeds such as size and hardness as well as nutritional composition. This could contribute to the exceptional observation to the pattern of seed powder produced in some of the maize varieties. This is confirmed by an observation during the sampling for damaged seeds (seeds with characteristic emergence holes) that *S. zeamais* has preference for small sized seeds in some of the maize varieties. This is not only true for *S. zeamais* in maize but for the rice weevil, *S. oryzea* (L.) in rice and other cereals (Gudrups *et al.*, 2001). This might explain the exceptions to the pattern of the quantity of powder produced by *S. zeamais* among the different maize varieties. *Sitophilus zeamais* infestation on large sized seeds produced greater quantity of powder than on small sized seeds. More powder was produced by highly susceptible varieties followed by susceptible varieties, moderately susceptible varieties and resistant varieties. This results is consistent with the number of F_1 progeny emergence, percentage seed damage and percentage weight loss.

5.7 Seed Germination

The observed differences in germination percentages showed that the eighteen maize varieties differed in susceptibility to *S. zeamais*. Percentage germination of the eighteen maize varieties was higher in non-infested seeds (before *S. zeamais* infestation) when compared with damaged seeds (after *S. zeamais* infestation). In damaged seeds high percentage germination was recorded for Aseda and TZE-Y POP STR when compared to the remaining varieties. This may be because of low number of weevils which completed development and emerged as adults from these varieties. These varieties also recorded the least percentage seed damage. Thus these varieties might have resistance factors which could result in less *S. zeamais* damage. Thus ability of the seed to germinate is not affected much by *S. zeamais* attack. On the other hand, germination percentage for Aburohemaa, Obaatanpa and Omankwa after *S. zeamais* infestation was drastically reduced because of higher number of weevils which completed development and emerged as adults from these varieties. These varieties with low germination percentages indicate their susceptibility to *S. zeamais*. This confirms the observations by Keba and Sori (2013) and Martha (2010) who stated that when the number of weevils which completed development and emerged as adults were high, the embryo was totally destroyed and for that reason seed germination was inhibited.

However there appeared to be exceptions to the pattern of seed germination in damaged seeds among some varieties. Some weevil damaged seeds germinated and this might be attributed to the fact that the weevils did not damage the embryo. This could account for the better percentage germination of Aburohemaa than Obaatanpa and Omankwa despite the higher number of F_1 progeny and greater percentage seed damage it recorded. Similar trend was observed in Ewul-Boyu, Bihilifa and WACCI-M-1205 which performed better in seed germination than other varieties even though they produced higher number of F_1 progeny compared to the other varieties. The most resistant maize varieties produced the highest percentage seed germination after *S. zeamais* infestation whereas the susceptible varieties recorded the lowest percentage seed germination.

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The significant differences and considerable variations observed among the maize varieties for seed moisture content, adult mortality rate, F_1 progeny production and population growth of the maize weevil, seed damage, seed weight loss, weight of seed powder produced, median development period, index of susceptibility, and seed germination before and after *S. zeamais* infestation suggest that response to the weevil is genotype dependent. These differences indicate that variability existed among the maize varieties evaluated that would allow for the identification of resistant genotypes. The results obtained from this study have indicated that there were variations in the degree of susceptibility of the maize seed varieties developed from the maize breeding programme of Crops Research Institute (CRI), Savanna Agricultural Research Institute (SARI) and West Africa Centre for Crop Improvement (WACCI) in Ghana. That is, the varieties had different degrees of resistance to this pest.

Aseda was the most resistant variety followed by TZE-Y POP STR which was found to be moderately resistant to *S. zeamais* attack among the different maize varieties. Five of the maize varieties, namely Kpari-Faako, Tintim, WACCI-M-1215, WACCI-M-1594 and Wang-Dataa were moderately susceptible; Abontem, Bihilifa, Ewul-Boyu, Sanzal-Sima, TZE-I 17, WACCI-M-1205, WACCI-M-1508 and WACCI-M-1510 were susceptible while Aburohemaa, Obaatanpa and Omankwa were highly susceptible to *S. zeamais* attack.

The study showed that infestation of maize in storage by *S. zeamais* progresses rapidly in the first two months of storage. The infestation process of *S. zeamais* is dynamic, thus population buildup of this pest is rapid with subsequent increase in seed damage, weight loss, frass weight and loss of viability. The internal infestation by *S. zeamais* influences physiological quality of the seed thereby reducing seed germination.

The results of the study demonstrated that insect resistant varieties would provide a sustainable way of reducing postharvest losses of seeds in storage and increase net grain yield among smallholder farmers in the country. Resistant varieties used in stored product insect pests' management is environmentally sound and economically justifiable option which should be promoted for the management of insect pests in stored maize, particularly for resource-poor subsistence farmers who keep grains on farm for future use as food and seed.

6.2 Recommendations

It is recommended that:

- ☐ Aseda and TZE-Y POP STR which demonstrated resistance to *S. zeamais* should be promoted or incorporated into breeding programmes to help minimize seed damage, weight loss and loss of viability incurred by farmers during storage.
- ☐ Kpari-Faako, Tintim, WACCI-M-1215, WACCI-M-1594, Wang-Dataa, Abontem, Bihilifa, Ewul-Boyu, Sanzal-Sima, TZE-I 17, WACCI-M-1205, WACCI-M-1508, WACCI-M-1510, Aburohemaa, Obaatanpa and Omankwa will require more protection in storage so as to preserve seed quality.
- ☐ Maize farmers in the country should concentrate their control on the management of *S. zeamais* at the beginning of seed storage if the seed is planned to be stored beyond three months.
- ☐ Maize farmers who store maize seeds for future use should dry their seeds to safe moisture contents and ensure that an equilibrium relative humidity is maintained throughout the storage period.
- ☐ Aburohemaa, Obaatanpa and Omankwa varieties which proved to be highly susceptible can be used as suitable substrates for feeding and breeding of *S. zeamais* and can be used as a source for rearing laboratory cultures of this pest.
- ☐ Further studies should be carried out on the resistant and susceptible maize varieties identified by this study in order to investigate the factors that confer resistance or susceptibility of these varieties to *S. zeamais*.

- Further studies should be carried out on the damaged seeds (weevil infested seeds) of some of the varieties which germinated as to whether they can develop into normal seedlings with better field establishment.
- The reaction of the different maize varieties to attack by first filial generation (F_1 generation) and subsequent generations (second filial generation) of *S. zeamais* should also be investigated.
- Supplementary testing of the reaction of WACCI-M-1215, WACCI-M-1594, WACCI-M-1205, WACCI-M-1508 and WACCI-M-1510 to storage insect pests should be carried out in order to generate data to support the laboratory findings of these hybrids for possible release in Ghana.
- This study may be repeated in the field under different storage systems in different agro-ecological zones under uncontrolled temperature and humidity conditions in the country over time to confirm the laboratory findings of this study.
- Studies on the reaction of seeds to storage pests are conducted and made a part of variety release proposal.

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APPENDICES

APPENDIX I: Analysis of variance for seed moisture content.

Source of Variation	d.f	s.s	m.s	v.r	Fpr.
Varieties	17	25.3298	1.4900	5.50	<.001
Residual	36	9.7533	0.2709		
Total	53	35.0831			

APPENDIX II: Analysis of variance for adult mortality.

Source of Variation	d.f	s.s	m.s	v.r	Fpr.
Varieties	17	10248.34	602.84	6.32	<.001
Residual	36	3432.15	95.34		
Total	53	13680.49			

APPENDIX III: Analysis of variance for days to first emergence.

Source of Variation	d.f	s.s	m.s	v.r	Fpr.
Varieties	17	678.667	39.922	14.57	<.001
Residual	36	98.667	2.741		
Total	53	777.333			

APPENDIX IV: Analysis of variance for number of F_1 progeny.

Source of Variation	d.f	s.s	m.s	v.r	Fpr.
Varieties	17	5.51087	0.32417	7.33	<.001
Residual	36	1.59222	0.04423		
Total	53	7.10309			

APPENDIX V: Analysis of variance for median development period.

Source of Variation	d.f	s.s	m.s	v.r	Fpr.
Varieties	17	388.167	22.833	2.52	0.010
Residual	36	326.667	9.074		
Total	53	714.833			

APPENDIX VI: Analysis of variance for index of susceptibility.

Source of Variation	d.f	s.s	m.s	v.r	Fpr.
Varieties	17	248.759	14.633	11.60	<.001
Residual	36	45.427	1.262		
Total	53	294.186			

APPENDIX VII: Analysis of variance for seed damage.

Source of Variation	d.f	s.s	m.s	v.r	Fpr.
Varieties	17	1608.82	94.64	7.09	<.001
Residual	36	480.80	13.36		
Total	53	2089.62			

APPENDIX VIII: Analysis of variance for seed weight loss.

Source of Variation	d.f	s.s	m.s	v.r	Fpr.
Varieties	17	151.626	8.919	2.85	0.004
Residual	36	112.662	3.130		
Total	53	264.288			

APPENDIX IX: Analysis of variance for frass weight.

Source of Variation	d.f	s.s	m.s	v.r	Fpr.
Varieties	17	66043.6	3884.9	9.00	<.001
Residual	36	15547.6	431.9		
Total	53	81591.3			

APPENDIX X: Analysis of variance for seed germination before weevil infestation.

Source of Variation	d.f	s.s	m.s	v.r	Fpr.
Varieties	17	1721.51	101.27	1.60	0.098
Residual	54	3425.42	63.43		
Total	71	5146.96			

APPENDIX XI: Analysis of variance for seed germination after weevil infestation.

Source of Variation	d.f	s.s	m.s	v.r	Fpr.
Varieties	17	6716.22	395.07	8.91	<.001
Residual	54	2394.92	44.35		
Total	71	9111.14			