Consumer Acceptability, Adaptability and Genetic Analysis of Orange pro-vitamin A maize hybrids in KwaZulu-Natal Province of South Africa

By

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GENERAL ABSTRACT

Diets of most people in sub-Saharan Africa are composed of mainly cereals that frequently lack most nutrients, such as Vitamin A. Vitamin A deficiency is the leading cause of preventable childhood blindness and increases the risk of death from common childhood illnesses, such as diarrhea. According to The World Health Organization, it affects 48% of children less than 5 years, in sub-Saharan Africa. This global challenge could be alleviated by breeding orange pro-Vitamin A maize hybrids, among other strategies. However, there was need to determine acceptance, adaptation and adoptability of these hybrids by the poor communities, in KwaZulu-Natal, and potential for improvement through breeding. Bio-fortification of maize with orange pro-vitamin A (PVA) changes maize grain colour, organoleptic properties (mainly flavor) and various agronomic traits due to effects of different genetic backgrounds. This study aimed at (i) establishing perception of consumers towards fresh PVA maize, (ii) determining agronomic performance of PVA hybrids across major production environments in South Africa, (iii) determining combining ability and gene action among a set of PVA germplasm and, (iv) identifying traits associated with high yield in PVA germplasm. Sensory evaluation and focus group discussions were conducted, in KwaZulu-Natal province, of South Africa. Results indicated acceptance of orange PVA maize by the end-users and reflected the effects of both age and gender. There were more women (79%) and men (76%) preferring boiled and roasted green mealies, respectively. Interestingly, the youth (18-35 years) had a higher acceptance of PVA maize compared to middle aged (36-60 years) and the elderly (61-75 years). However, focus group discussions revealed that farmers had concerns of agronomic adaptability, economic value, and food value of the PVA maize. The study showed potential for PVA maize in its fresh form for utilization as a food and cash crop. To understand the genetics of PVA maize, crosses among 10 PVA inbred materials with 10 inbred materials from diverse genetic backgrounds were conducted using a lines by tester mating scheme. The resultant 100 single cross hybrids were evaluated using a 10 x 10 α-lattice design with two replications across four environments in South Africa. There were significant differences among hybrids for grain yield and agronomic traits. The lines and testers main effects, and line x tester interaction effects, as well as their interactions with the sites were significant ($P < 0.05$) for grain yield and associated traits. The predominant additive gene action for most traits including grain yield allowed selection of desirable inbred lines. The significant ($P<0.05$) genotype plus genotype x environment interaction enabled identification of stable and high yielding hybrids. The agronomic performance of a set of PVA hybrids were compared to white and yellow maize

counterparts to understand the yield gap among them. Generally, PVA hybrids had yields that were lower than that of the white and yellow maize types, indicating opportunity for further breeding gains. Although several traits such as longer ears, high shelling percentage, and resistance to diseases were correlated with yield, the lower grain yield of PVA hybrids was associated with high root and stem lodging. There is need to take advantage of the predominant additive gene action to develop inbred lines that can produce stable and high yielding hybrids through fixing lodging related traits in PVA. Overall the study confirmed the opportunity for deploying orange pro-vitamin A maize hybrids and contribute to alleviation of Vitamin A deficiency in KwaZulu-Natal.

DECLARATION

I, **Fikile Nozipho Pricilla Qwabe**, certify that this is my original work and it contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by any other person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of KwaZulu-Natal and where applicable, any partner institution responsible for the joint-award of this degree. I also declare that;

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Signed:

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As the candidate's supervisors, we agree to the submission of this thesis

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DEDICATION

I would like to dedicate this work to my beloved parents Mr R.M and Mrs. S.D Qwabe who regretfully did not live to see this work, which resulted from their gift of love to me for many years. I thank God for them even though the time I spent with them was too short.

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AD: Anthesis date

AMMI: Additive main effect and multiplicative interaction

ANOVA: Analysis of variance

ASI: Anthesis-silking interval

CEC: Cation exchange capacity

CIMMYT: International Maize and Wheat Improvement Center

EH: Ear height

EL: Ear length

EPO: Ear position

EPP: Ear prolificacy

ET: Turcicum leaf blight

FGDs: Focus group discussions

GCA: General combining ability

GEI: Genotype by environment interaction

GGE: Genotype plus genotype by environment interaction

GY: Grain yield

LAN: Lime ammonium nitrate

LSD: Least significant difference

MAP: Magnesium ammonium phosphate

MOI: Grain moisture content

OFSP: Orange fleshed sweet potatoes

PH: Plant height

QPM: Quality protein maize

RL: Root lodging

SCA: Specific combining ability

SD: Silking date

SL: Stem lodging

SP: Shelling percentage

SREG: Site regression

SSA: Sub-Saharan Africa

SVP: Singular value partitioning

TL: Total lodging

VAD: Vitamin A deficiency

CHAPTER 1: INTRODUCTION

1.0 Introduction

1.1 The significance of maize in sub-Saharan Africa

Maize (*Zea mays* L.) is currently being cultivated on over 100 million hectares in 125 developing countries and is among the three most widely grown cereal crops worldwide (FAOSTAT, 2013) with a world production of 981 million tons of grain in 2014 (FAOSTAT, 2015). World-wide, maize ranks number three after rice and wheat as the major source of calories (Bänziger *et al.*, 2006) and is the major grain crop produced in South Africa (Jones, and Thornton, 2003). Maize is the major grain crop in southern Africa, where it is mainly grown for food (FAOSTAT, 2013). However, during years of surplus, maize can be sold to raise income and also used to feed livestock. This crop has the highest per capita consumption compared to other cereals in the region (Setimela *et al*., 2017a). Pingali and Pandey (2007) noted that the demand of maize in the world will double by 2050. Approaches that can improve maize grain yield such as based on the modification of the environment or the genetic make-up are required. Maize will remain a preferred crop by many rural communities because of several factors that include ease of propagation, harvest, and handling, long storability and ease of processing into various products.

1.2 Prevalence and effects of vitamin A deficiency in Africa

Africa is leading in terms of malnutrition (Nyakurwa *et al*., 2017), and vitamin A deficiency (VAD) prevalence is high (FAOSTAT, 2013). Vitamin A deficiency is a major public health challenge in developing countries, causing VAD related illnesses in about 127 million children below the age of five and more than seven million pregnant women; especially in sub-Saharan Africa (Aguayo and Baker, 2005). The main basic factor leading to VAD is consumption of a diet that is chronically deficient in vitamin A. For example, most rural communities are dependent on the ordinary white maize as the major source of calories, and thus have limited access to the dietary requirements for vitamin A (Bauernfeind, 1972; Nyakurwa *et al*., 2017). This can result in reduced body reserves and failure to meet the body's physiological needs such as tissue growth, normal metabolism and resistance to infection (Gibney *et al*., 2008). According to the World Health Organization (WHO), severity of VAD can lead to disorders, such as xerophthalmia, anaemia, and weakened host resistance to infection, night blindness, loss of appetite and poor growth rate (Pillay *et al*., 2011). Risks associated with VAD disorders are to a great extend raised by low vitamin A intakes during demanding life situations such as childhood, infancy, pregnancy and lactation (Pillay *et al*., 2011).

World development and health agencies have responded to the problem of VAD by distributing vitamin tablets and fortifying processed foods. However, according to Kapinga *et al.* (2003), many resource poor rural families fail to sufficiently and regularly access these supplements as a result of poor infrastructure characteristic to remote areas of sub-Saharan Africa (SSA). The dent types of white maize grain are produced and consumed in larger amounts compared to the flint types due to their higher grain yields (Setimela *et al*., 2017a). However, white maize lacks the pro-vitamin carotenoids, which are the precursors of vitamin A (Nuss and Tanumihardjo, 2010). Crops that have high content of pro-vitamin A carotenoids include orange fleshed sweet potatoes, carrots and orange maize.

1.3 Problem statement and justification

The diets of most people in SSA are composed mainly of cereal grains, with limited access to other sources of proteins and vitamins (Nyakurwa *et al*., 2017; Setimela *et al*., 2017b). Amongst the cereal grains, in SSA, white maize is a leading staple and as such, it is a key food security crop. On the other hand, white maize grain, like most other cereal grains, is deficient in several nutrients, including vitamin A. Research efforts in maize should therefore focus on its bio-fortification. One such approach is to introduce orange maize. The advantage of bio-fortified maize is that farmers are already growing and widely consuming maize (Setimela *et al*., 2017a), and thus introduction of its alternative form could offer an excellent buy-in to increase the adoption. However, where ever there is a proposal to change the common diets of people, there will always be questions pertaining to acceptability by the consumers. Usually consumers become accustomed to the product taste, appearance and other factors, which they deem necessary. Consumer perception in new products must be a key consideration in attempts to increase the adoption of new technologies (Pillay, 2011). This therefore raises the need to understand the perceptions of farmers towards orange maize, which is rich in pro-vitamin A.

The concept of general combining ability and specific combing ability was widely used to elucidate gene action and also in identifying suitable parents for use in the development of desirable hybrids (Sprague and Tatum, 1942). When inbred lines are developed, their combining ability should be assessed in order to identify desirable parents and hybrids. Furthermore, understanding the nature of gene action can also provide useful information that is needed in designing breeding programmes (Derera *et al*., 2007; Gasura *et al*., 2013). In this study, the combining ability and gene action controlling the major traits in a given set of PVA germplasm was unknown. Thus, understanding the combining ability and gene action in this set of germplasm would provide the required genetic information in the selection of best parents, hybrids and breeding strategy for PVA maize development.

When new hybrids are developed, such as the current PVA hybrids, there is need to assess their performance (Gasura *et al*., 2015). This information is critical in identifying stable and high yielding hybrids that can be grown across environments. Furthermore, it can also to identify hybrids that are adapted to particular production environments (Yan and Tinker, 2006). Recommendation of an appropriate variety for farmers in particular areas is essential in increasing grain yield that can be obtained in that area.

Secondary traits have been widely used in indirect selection for grain yield in many studies (Banziger *et al*., 2006; Gasura *et al*., 2014). The efficiency of selection can be greatly improved when indirect selection methods are used to complement selection based on grain yield alone (Gasura *et al*., 2014). This is because, grain yield has low heritability whereas some secondary traits have high heritability and could be relatively easier to measure. Thus, identification of secondary traits that are associated with high grain yield in pro-vitamin A hybrids is essential in predicting the traits that could be used in the future to complement selection based on grain yield. Improving the efficiency of selection could hasten the breeding process in the future.

1.4 Research objective

The major objectives of this study was to determine the potential of pro-vitamin A maize as a substitute of ordinary maize in South Africa based on its acceptability, genetic potential and grain yield stability across major production environments.

1.4.1 Specific objectives

The specific objectives of the study were to:

1) To establish perception of consumers towards fresh orange pro-vitamin A maize grain.

2) To determine agronomic performance of pro-vitamin A hybrids across major production environments in South Africa.
3) To determine combining ability and gene action controlling of pro-vitamin A trait in maize
4) To identify traits associated with high yielding potential in pro-vitamin A maize germplasm across four environments in South Africa.

1.4.2 Research questions

The following research questions were tested:

1) What are consumer perceptions towards fresh orange pro-vitamin A maize, and is this grain type sensorial acceptable to consumers?
2) Are there some pro-vitamin A hybrids with high grain yield and stability across the major production environments in South Africa?
3) Is there desirable combining ability and what gene action is controlling pro-vitamin A trait set of pro-vitamin A germplasm?
4) Are there secondary traits associated with high yield potential in pro-vitamin A germplasm across four environments in South Africa?

1.4.3 Research hypotheses

The following research hypotheses were answered in the study:

1) Consumers have a positive perception towards fresh pro-vitamin A maize grain and the grain is sensorial acceptable to consumers.
2) Some pro-vitamin A hybrids have high grain yield and stability across the major production environments in South Africa.
3) There is desirable combining ability and mainly additive gene action among a set of pro-vitamin A trait in maize
4) There are some secondary traits associated with high yield potential in pro-Vitamin A germplasm across major production environments in South Africa.

1.5 Thesis outline

The thesis chapters are presented in the following order:

Chapter 1: **General Introduction**

This chapter provides the study background and outlines the scope, aim and objectives, problem statement, significance of the study and outline of the thesis.

Chapter 2: **Literature Review**

This chapter presents the theoretical background of the study by reviewing literature pertaining to the importance of maize in sub-Saharan Africa, known perceptions about different types of maize, general and specific combining ability, gene action controlling major traits in maize, and the concept and causes of genotype plus genotype by environment interaction. Associations of some secondary traits with maize grain yield are also reviewed.

Chapter 3: **Establishing perception of consumers towards pro-vitamin A fresh maize**

This chapter outlines the survey design, data collection and capturing methods and data analysis approaches used. The survey results on consumer perception towards pro-vitamin A fresh maize are presented. The discussion and conclusions are provided.

Chapter 4: **Determining agronomic performance of pro-vitamin A hybrids across major production environments in South Africa**

This chapter outlines the design of field experiments, data collection and data analysis approaches deployed. The results, discussion and conclusion on the genotype by environment interaction patterns as well as high yielding and stable hybrids are provided.

Chapter 5: **Combining ability and gene action among a set of pro-vitamin A germplasm**

This chapter outlines the field design, field data collection and data analysis approaches used. The results on combining ability and gene action are provided. These are followed by their discussion and conclusions.

Chapter 6: Identifying traits associated with high yielding potential in pro-vitamin A germplasm across four environments in South Africa

This chapter describes the experimental design, data collection and analysis methods used. The results on the association of various secondary traits with grain yield are presented. These are followed by their discussion and conclusions.

Chapter 7: General Discussion, Conclusions and Recommendations

The results of the study are discussed in this chapter, and it also provides a general discussion of the findings provided by the research. This chapter draws the conclusions that were revealed from the study, summarizes the key findings of the research chapters, and presents the overall conclusions and recommendations for future breeding programs and research.

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Chapter 2 **LITERATURE REVIEW**

2.1. Introduction

This chapter reviews literature on importance of maize, importance of pro-vitamin A maize in human diets, the need for bio-fortification in crops such as maize, past efforts in making crop bio-fortification, past and present efforts in bio-fortification of maize, factors that influence farmers perceptions and acceptability of bio-fortified crops, importance of raising awareness campaigns and inclusion of farmers in variety selection, past efforts in palatability studies in South Africa It also reviews literature on combining ability studies in maize, applications of combining ability in selection of parents and hybrids, applications of combining ability in gene action studies, methods of studying combining ability in crops such as maize, line by tester mating scheme, combining ability in quality protein maize and pro-vitamin A maize. It further reviews approaches applied in understanding genotype by environment interaction, methods of studying genotype by environment interaction, additive main effect and multiplicative interaction model, the genotype plus genotype by environment interaction (GGE) model, genetic gains in breeding quality protein maize and pro-vitamin A maize and trait association and use of indirect selection in plant breeding. Lastly, conclusions are drawn in relation to objectives of the research, and knowledge gaps identified are highlighted.

2.2 Importance of maize with elevated levels of pro-vitamin A

Maize (*Zea mays* L.) is being grown on over 100 million hectares of land in more than 125 developing nations (FAOSTAT, 2013). In terms of world-wide production and consumption maize ranks number three after rice and wheat (FAOSTAT, 2013) and has an estimated total word production of 981 million tons (FAOSTAT, 2015). Maize production and demand will double by 2050 (Pingali and Pandey, 2007) and its production must be increased to meet the global needs. This will however require harnessing of strong policies and proper technologies (Shiferaw *et al.,* 2011). Maize is the primary major staple food in developing countries, especially in southern Africa, where it is mainly used as major source of food, feed and energy source (Setimela *et al*., 2017a). The high productivity per unit area in maize makes it an attractive crop to produce (FAOSTAT, 2013). In Africa, the top five leading producers of maize are South Africa, Tanzania, Malawi, Ethiopia and Kenya with 22.64%, 8.66%, 7.93%, 7.83%

and 6.99% production share (FAOSTAT, 2013). However, the top five consumers of maize in Africa are South Africa, Malawi, Kenya, Zimbabwe and Ethiopia with 229, 195, 171, 125, and 94 kg per capita per year consumption rate (FAOSTAT, 2013).

Vitamin A deficiency (VAD), is one of the major challenges that face resource limited farmers in sub-Saharan Africa (Stein, 2010). Vitamin A deficiency is associated with several effects of malnutrition that include disorders such as xerophthalmia, anaemia, and weakened host resistance to infection, night blindness, loss of appetite and poor growth rate (Pillay, 2011).

There are several options that can be deployed to combat VAD. Some of these include supplementation of the diets with vitamin A tablets, diversification of crop production to produce those crops that are high in pro-vitamin A, such as orange fleshed sweet potatoes (OFSPs), carrots and pro-vitamin A (orange) maize (Mwanga *et al*., 2009; Stein, 2010). The advantages of pro-vitamin A maize are that it is the widely grown crop and its adoption could be high since most African diets are composed of maize and its products. However, adoption would remain a key issue to consider since the consumer preferences vary. For example, studies on consumer preferences of pro-vitamin A maize survey conducted in KwaZulu-Natal, South Africa showed cultural preference for white maize over pro-vitamin A maize (Pillay, 2011). This trend is a major setback since most women and children are under-nourished since they are fed with diets that are frequently lacking in vitamin A (Aguayo and Baker, 2005).

2.3 Bio-fortification in crops including maize

2.3.1 The need for bio-fortification in crops

Most of the resource limited farmers are highly dependent on maize as their source of food. However, ordinary white maize, is generally low in vitamin A (Bauernfeind, 1972; Aguayo and Baker, 2005). The human population frequently fed to such kind of maize diet will be deficient in the vitamin A, and frequently suffer mal-nutrition problems related to VAD such as increased susceptibility to diseases, night blindness and reduced growth rate (Nyakurwa *et al*., 2017). Lactating mothers and pregnant women are highly affected by VAD. Cheaper options are required for rural farmers whose income levels are generally too low to purchase other sources or supplements. Orange maize is one of the best alternative since it provides the cheapest and the most preferred alternative source of vitamin A. The advantage of this technology is that it is embedded in the ordinary crop which farmers are used to in terms of consumption and production (Aguayo and Baker, 2005).

2.3.2 Past efforts in crop bio-fortification

The crop based approach to combat vitamin A deficiency is now an international trend (Kapinga *et al*., 2003). Past efforts in sub-Saharan Africa in terms of bio-fortification were focused on orange-fleshed sweet potatoes. Since the year 2001, forty partner agencies from nutrition, health, and agricultural sectors have been working together to extend the impact of OFSP in Tanzania, Ghana, South Africa, Mozambique, Uganda, Kenya, and Ethiopia, under the Vitamin A for Africa (VITAA) umbrella (Kapinga *et al*., 2003). Evaluation studies of OFSP varieties have been carried out in several countries which include Uganda, Kenya, Mozambique, South Africa, Rwanda, Tanzania, Zambia and Malawi among other countries (Kapinga *et al*., 2003) and recently in Zimbabwe (Nyakurwa *et al*., 2017). The approach used to carry out these evaluations has been mainly participatory where farmers host the sweet potato trials, and then varieties are evaluated for adaptability and acceptability and best performing varieties are recommended for different agro-ecological areas.

2.3.3 Past and present efforts in bio-fortification of maize

Maize has been since realized as the most important crop in the sub-Saharan Africa. To this, regards, several efforts steered by the International Maize and Wheat Improvement Centre (CIMMYT), were focused on the bio-fortification of maize, which started on improving the protein quality (quality protein maize) during the past three decades (Setimela *et al*., 2017b) and then recently the improvement in the vitamin A content. In addition to the CIMMYT, the bio-fortification of maize is being jointly implemented by the private and public sectors that include universities, national research institutions and private companies across Africa. It is in line with these efforts that the breeding efforts at the University Of KwaZulu Natal South Africa became aligned towards vitamin A bio-fortification of maize using widely adapted germplasm sourced partly from CIMMYT and its research partners.

During the early years of research, maize bio-fortification focused on improving its protein quality. Maize has protein of low nutritional value compared to legumes (Lauderdale, 2000).

The protein amount and quality is undermined by low levels of essential amino acids, namely tryptophan and lysine, especially for monogastric animals (Vasal, 2000). The great breakthrough in maize protein quality improvement was as a result of the discovery of a natural maize mutant during the 1920s which had elevated levels of essential amino acids, tryptophan and lysine. It was named *opaque-2* due to its inability to transmit light when put on a light box (Vasal, 2000). Normal maize is homozygous dominant O_2O_2 for the *opaque-2* gene and it is translucent under light whilst the *opaque-2* mutant is homozygous recessive (o_2o_2) (Vivek *et al*., 2008). This mutant underwent intensive development to eliminate some of the deleterious effects associated with it, such as increased disease susceptibility and was later termed quality protein maize (QPM) by the International Maize and Wheat Improvement Centre (CIMMYT) (Lauderdale, 2000). The *opaque-2* gene has been widely used in breeding programs to convert non-QPM maize populations to QPM versions which are better performing and adapted through the conventional breeding methods (Vivek *et al*., 2008).

The impact of QPM was widely demonstrated in animal feeding experiments. Pigs and broiler chickens fed to QPM had double growth rate and much increased carcass weight compared to the livestock fed on the normal maize. In humans, the effects of QPM are confounded by other sources of protein which are simultaneously included in the diets. However, the effects of kwashiorkor and other malnutrition challenges were greatly reduced in the human sub-populations fed to QPM (FAOSTAT, 2015).

In maize, the vitamin A bio-fortification is fairly new. This work started with some attempts to understand the pathway of pro-vitamin synthesis. Several genes were found to be affecting this pathway and their control was mainly additive. In this regard, some breeding efforts at CIMMYT resulted in the development of bio-fortified maize hybrids that were released in various countries in sub-Saharan Africa such Zimbabwe and Zambia. Studies on acceptability are highly limited and these initiatives have been lagging in South Africa, thus raising the need of this study.

2.4 Farmer preferences and perceptions

2.4.1 Factors influencing farmers perceptions and acceptability of bio-fortified crops

Acceptability studies done by several researchers found out that the success of any new variety depends not only on agronomic characteristic but also on its acceptability by consumers in terms of sensory and utilisation characteristics (Setimela *et al*., 2017b). For example, Niringiye et al. (2014) reported that the main criteria used by farmers on orange fleshed sweetpotato variety choice are high yield followed by early maturity, tolerance to diseases, sweetness, low fibre content, and long underground storage. Tumwegamire *et al*. (2014) pointed out taste as one of the important attributes determining acceptability of a variety by farmers, emphasising that taste can be as important as yield when farmers choose a variety to adopt or to reject.

According to Kapinga *et al*. (2003) the impact of OFSP varieties replacing white fleshed varieties is great. As reported by Low *et al*. (2009), a great proportion of the population at risk of VAD in countries with high sweet potato production density as Burundi, Rwanda and Uganda has fully benefited from replacement of white fleshed varieties with OFSP varieties Orange maize is an already widely grown crop as a primary food crop throughout almost all of SSA; therefore, promoting a shift in dietary practices, such as changing varieties is likely to be easier than introducing a completely new food into the diet (Tomlins *et al*., 2007). Therefore, the impacts of OFSP are expected to be great in the SSA region where the majority of the populace depends on maize as the major source of food and food products.

2.4.2 Importance of raising awareness campaigns and inclusion of farmers in variety selection

Participatory variety selection has been highly instrumental in the adoption of new varieties of various crops (Low *et al*., 2009) Participatory evaluation involves establishment of trials, data collection and data analysis with the farmers. Another way to assess the preference of end-users is the use of surveys (Pillay, 2011). This technique was used in this study to assess if the farmers have positive perceptions.

2.4.3 Past efforts in palatability studies in South Africa

In South Africa, a study conducted by Pillay (2011) showed that there are cultural perceptions on maize types. Farmers preferred white maize to orange maize. However, this was a pilot study, and there could be huge prospects that over time farmers change their perceptions in line with education. Studies conducted in hospitals showed that people were able to adjust their diet and physical needs based on the diseases affecting them. In this regard, there is huge prospect that over time, farmers will change their perception and accept orange maize varieties and then improve their nutrition and associated benefits such as improved health and productivity.

2.5 Combining ability studies in maize

2.5.1 The concept of combining ability

The concept of combining ability was described by Sprague and Tataum (1942). This concept is now widely used to identify desirable parents for use in hybrid production (Griffing, 1956) as well as in elucidating the gene action governing traits under study (Sprague and Tataum, 1942). The importance of combining ability studies in genetic studies can be estimated based of the number of researches done in the area (Sofi and Rather, 2006). To date, several combining ability studies have been widely conducted in different crops that include maize (Derera *et al*., 2007, Gasura *et al*., 2013; Pswarayi and Vivek, 2008). In combining ability studies, the terms general and specific combing ability are widely used. These two terms are used in estimating the major gene action controlling a trait and in the selection of desirable parents and hybrids.

2.5.2 Applications of combining ability in selection of parents and hybrids

Parents are widely selected based on their desirable general combing ability. General combining ability (GCA) is the average performance of a line in a series of hybrid combinations and it is directly related to the breeding value of a parent and is associated with additive genetic effects (Griffing, 1956). The GCA effect can be near zero, negative or positive depending on the trait. A zero or close to zero GCA indicates that the mean of a line is not different from the average mean of all crosses. A parent with positive GCA effect has a tendency of increasing the mean value while a parent with a negative GCA effect decreases the mean value. The type of the desirable GCA effect depends on the trait. For example, when breeding for high grain yield, the GCA effects should be highly positive since more grain yield is desirable while the when breeding for pest or disease damage, negative GCA effects are desirable since they have more tendency of decreasing the level of damage. The choice of parents will thus be based on the GCA values and should have high positive or negative values for the favourable traits. Thus, this criteria is very essential in the choice of parents for use in population development.

Bernardo (2002) emphasised a cross between good by good in population development. The good in this case refers to the GCA effects based on the testcross performance of a given set of inbred lines. Half-sib (hybrids with one common parent) families are used to estimate GCA. Therefore, the average performance of all F_1 crosses resulting from a particular line when randomly crossed with a series of lines in a population is the estimate of GCA and is expressed as a deviation from the population mean. Best parental lines to be used in inbred line development are selected based on GCA.

Specific combing ability is the term used to describe the extent of deviation of the hybrid mean performance from its predicted value based on the general combining ability effects of the lines and the population mean (Griffing, 1956). The specific combining ability effects are used to select desirable hybrids. Likewise, positive and negative SCA effects are used in the choice of desirable hybrids. In hybrid selection, however, it should be noted that high SCA values should be associated with high mean performance to justify a hybrid as a desirable one (Pswarayi and Vivek, 2008). Large negative or positive SCA values suggest that the inbred lines would be coming from different heterotic groups. High heterosis as exhibited by large SCA effects is desirable in hybrid breeding. Based on this approach, several efforts have been mounted into classification of maize inbred lines into heterotic groups.

Sprague and Tatum (1942) explained the applications of GCA and SCA variances in suggesting the predominant gene action governing a trait. Presence of significant GCA variance suggests the preponderance of additive genetic effects thus; significant and large GCA variances are correlated with narrow sense heritability (Amiruzzaman *et al.*, 2013). The presence of significant SCA variances indicates non-additive effects, which are mainly due to dominance and epistasis taken together. However, it should be noted that epistasis is highly negligible in most studies. Falconer, 1961 Specific combining ability can be obtained from full-sib families and is highly positively correlated with heterosis. In studies where there is no information about SCA effects, heterosis is used to select some superior crosses (Machado *et al*., 2009). High SCA estimates (negative or positive) suggest superior crosses and suggest that the inbred lines come from different heterotic groups. Superior hybrids are thus selected based on favourable SCA effects (Pswarayi and Vivek, 2008;Machado *et al*., 2009;).

2.5.3 Applications of combining ability in gene action studies

The ratio of the GCA variance to the SCA variance was reported by Baker (1989) to be useful in suggesting the major gene action under control. When the ratio is one or closer to unity it suggest that both additive and dominance gene actions are under-play in the control of the trait. However, when the ratio is above one, it suggests that there is more additive gene action compared to non-additive (dominance) gene action. More so, when the ratio is below unity it shows that non-additive gene action would be greatly controlling the trait (Baker, 1989).

The relative importance of the gene action governing the trait is essential in choosing the type of cultivar to produce (Griffing, 1956). For example, pure lines must be developed when there is more additive, while hybrids are desirable when there is high non-additive as well as non-additive by non-additive type of epistasis. In hybrid maize breeding, the development of hybrids is justified by the predominance of non-additive gene action to additive gene action in controlling maize grain yield. However, in some rare situations such as in the forages, the occurrences of both additive and non-additive gene action justify the creation of synthetic varieties that utilizes all possible types of gene action.

The type of gene action also has influence on the choice of breeding method. When additive gene action is high, narrow sense heritability would be also high, and thus the selection can be based on single plants in non-replicated plots in single environments. However, in situations that reflects more of non-additive gene action, the narrow sense heritability would be low. When narrow sense heritability is low as in situations of grain yield, selections for that particular trait must be based on a plots basis (not individual plants), as well as replicated plots in many environments (Bernardo, 2002).

2.5.4 Methods of studying combining ability in crops such as maize

Several techniques are suggested for the estimation of combining ability (Hallauer *et al*., 2010). These include the top cross method, North Carolina design by Comstock *et al.* (1949), poly cross technique, diallel cross analysis by Griffing (1956), line × tester analysis by Kempthorne (1957), partial diallel cross by Kempthorne and Curnow (1961), and triallel cross by Rawlings and Cockerham (1962) are used to estimate combining ability. The line x tester, North Carolina design 2 and the diallel mating schemes have been widely used to study the combining ability effects of a set of the inbred lines. The line x tester mating scheme involves mating a set of inbred lines with either a common tester that could be narrow based (inbred line or hybrid) or broad based (open pollinated variety). This scheme only differs with the NC2 mating design in that in the later some lines are designated as males while others as females. The choice of males and females would be based on a particular reason such as when the female have high yield potential whereas the males are contributing high levels of resistance to a particular disease or pest. The line x tester mating scheme and the NC2 mating scheme have advantages of reducing the number of crosses that could be produced from other designs such as the diallel mating scheme.

The choice of a tester is essential in a line x tester mating scheme (Kempthorne (1957). In general, a tester must have low grain yield and poor performance in other traits to allow a quick identification of potential inbred lines. Furthermore, a tester must be broad based, to allow discrimination of a large number of inbred lines and lastly a tester must have wide adaptability (Pswarayi and Vivek, 2008). In some other rare cases, where the aim is to improve a given hybrid, an inbred line could be used as a tester so as to quickly identify lines that can complement the desirable tester.

Testers can be used to classify maize lines into specific heterotic groups and to identify better germplasm for a given breeding purpose. For example lines with desirable positive or negative GCA effects are selected based on the needs of a given breeding programme. Pswarayi and Vivek (2008) identified a suitable tester from their choice of potential testers based on three characteristics; display of high desirable GCA effects, classification of lines into heterotic groups, and *per se* grain yield.

2.5.5 Line by tester mating scheme

The line by tester mating scheme was proposed by Kempthorne (1957) and can accommodate a large number of genotypes. This method can also provide information about the efficacy of lines for use as parents in a hybridization programmes (Hallauer *et al.*, 2010). Line by tester mating scheme, involves lines and testers, is an extension of the analysis of two factor factorial experiment (Fisher, 1992). All lines are crossed to each of the testers and thus line by tester full-sib progenies are generated. Developed hybrids together with parents or without parents, are evaluated in replicated trials using a suitable experimental design (Comstock *et al.*, 1949). All inbred lines are mated to all testers and the single cross hybrids are evaluated to provide essential information about GCA effects of the lines and testers, as well as SCA effects due to line by tester interaction.

2.5.6 Combining ability of quality protein maize and pro-vitamin A maize

Combining ability studies among the PVA and QPM germplasm is not well documented (Gregorio, 2002; Egesel *et al*., 2003). However, the use of diverse maize inbred lines has a huge chance of getting heterosis. This formed the basis of crosses between PVA and PVA, PVA and QPM as well as PVA and normal maize. When desirable combinations are obtained, then the lines can be converted into the desirable background of either QPM or PVA. In hybrid breeding, the major task is to focus on combinations that can improve the major traits that are highly quantitatively inherited such as grain yield followed by the improvement of the minor traits through the backcross breeding scheme through backcrossing or gene editing.

2.6 Genotype by environment interaction

2.6.1 Approaches applied in understanding genotype by environment interaction

Genotype by environment interaction (GE) refers to the differential responses of given cultivars under different sets of environments (Finlay and Wilkinson, 1963). Genotypes are thought to possess a different set of genes that are differentially expressed in different environments where given stimuli is found (Yan and Kang, 2002). When a given genotype has the genes required to respond in a given environment, the yield is retained, while when the genes are absent the yield decreases thus a different combinations of genes in given set of environments results in the GE. The GE can be studied through conducting multi-environmental trials (MET).

In given MET, the occurrence of GE must be detected and this can be achieved by using techniques such as the analysis of variance. When GE is absent, this offers an excellent option to plant breeders where the evaluation of cultivars should be done only in a single environment (Yan and Tinker, 2006). However, when GE is present, it is worthy checking if it is of rank or magnitude (Yan and Tinker, 2006). When GE reflects only the change of magnitude, it must be handled in the same way as the case when GE is absent. However, cross over GE, that involves the change in cultivar rank across environment is of a major concern in plant breeding.

Yan and Tinker (2006) reported that when GE is present and is of cross over type, the major causes of GE should be identified.

Either predictable or non-predictable factors are the major causes of GE. Examples of predictable factors include the soil type and the management system while non-predictable factors include the rainfall amount and occurrence of biotic stress (Gasura *et al.*, 2015). Thus, when crossover GE is present, Bernardo (2002) reported that it could be exploited or reduced. Thus, GE can be reduced by sub-dividing the test locations into mega-environment in which the extent of GE would be greatly reduced. Suitable varieties for each mega-environments are identified, and these are normally called adapted varieties. However, this must be done if there are many test locations and the pattern of mega-environment delineation must be repeatable across years. Thus single year MET data is usually insufficient for mega-environment delineation. Another approach of handling cross over GE is by exploiting it. This involves selection of high yielding and stable varieties across the test locations and years. This approach is normally the most rationale in METs unlike the mega-environment delineation which has been highly used.

2.6.2 Models of studying genotype by environment interaction

Models such as the additive main effect and multiplicative interaction (AMMI) and the genotype main effect plus the GE (GGE) have been widely used. Studies indicate that AMMI and GGE remain unclear in terms of differences in their effectiveness (Gauch *et al*. 2008). The advantage of the AMMI is that it incorporates Gollob's F-test (Gollob, 1978) that can be used to determine the number of significant principal components that should be added in the model (Gauch, 2013; Zobel *et al*., 1988). Furthermore, the AMMI model has in built methods of model diagnostic that determine the number of principal components to retain in the model (Gauch, 2013). However, the major weakness of AMMI is that it requires the use of balanced data coming from a randomized complete block design. On the other hand, the GGE biplots can be done using adjusted means coming from any design, making them more useful for modern field designs such as the apha-lattice designs that can handle any number of genotypes per given time.

2.6.3 Additive main effect and multiplicative interaction model

The additive main effects and the multiplicative interaction (AMMI) model comprise genotype main effect, environment main effect and the interaction with 0-F interactive principal components axis (IPCA) (Crossa, 1990). The AMMI model is widely used to clarify GE and to improve accuracy of yield estimates and used for better understanding of genotypes, environments and the complex of their interactions which essentially aid in assigning genotypes to environments they are adapted to and in identifying the best environment for evaluation of genotypes (Gauch, 2013). Crossa *et al*. (1990) indicated that the AMMI model can be used to analyse the GE, identify superior maize hybrids, and to select for the maize hybrid in the specific test environment. Depending on the number of principal components used in the study, the AMMI models can range from AMMI (0) to AMMI (n). In the current study the AMMI (2) model was adopted since it was found to be adequate based on the Gollob F-test (Zobel, 1988).

2.6.4 The genotype plus genotype by environment interaction (GGE) model

The difference of the AMMI and the GGE models is that the GGE is based on environment-centred PCA, whereas AMMI model refers to double-centred PCA (Yan and Tinker, 2006). The GGE kind of approach is highly useful in; (i) visualizing the patterns of the interactions, (ii) identifying ideal testing environments based on their discriminating and the representativeness and (iii) can identify high yielding and stable genotypes (Yan and Tinker, 2006; Yan and Kang, 2002).

2.7 Genetic gains in breeding quality protein maize and pro-vitamin A maize

Plant breeding is a process that is on going. The progress in terms of plant breeding can be obtained in terms of the genetic gains achieved per cycle per year. In maize breeding, the rates of genetic gains were quickly achieved with changes from open pollinated maize to hybrids, and then with the use of proper management such as fertilizers and proper plant densities (Duvick and Cassman, 1999) during the fresh revolution followed by the use of molecular markers and high throughput phenotypic techniques. The rate of genetic gain in tropical maize was estimated to be low. Masuka *et al*. (2017a, b) recently evaluated genetic gains in the CIMMYT east and southern Africa maize hybrid and OPV breeding programs during the period 2000-2010. Hybrid gains in grain yield under optimal, managed drought, random drought, low N and maize streak virus (MSV) were estimated at 1.4%, 0.85%, 0.85%, 0.62%

and 2.2% per season, respectively. In terms of realised gains, yields were estimated to have increased by 109.4 kg ha^{-1} yr^{-1}, 32.5 kg ha^{-1} yr^{-1}, 22.7 kg ha^{-1} yr^{-1}, 20.9 kg ha^{-1} yr^{-1} and 141.3 kg ha^{-1} yr^{-1}, respectively. Similar rates of genetic gains in tropical maize were reported by Setimela *et al*. (2017a). However, QPM and PVA maize hybrids are rare, and their genetic gains were not estimated (Setimela *et al*., 2017a).

2.8 Trait association and the use of indirect selection in breeding

In crop breeding, some traits could be highly correlated. There are several causes of correlation that include the genetic correlation and pleiotropic effects (Falconer, 1961). Correlation among traits has been widely used in aiding selection. Complex traits such as grain yield are controlled by many genes and thus their heritability is low. When heritability is low the selection of the trait becomes very difficult since it requires many plants per plot, many replications in space and time. However, increasing the number of plants to evaluate and the number of replications is always costly in a breeding programme. Therefore, if there is correlation of the primary trait with a secondary trait, then a secondary trait could be used to aid the efficiency of selection by basing the selection on both the primary and the secondary trait. In some modern breeding programmes, a selection index is highly used for indirect selection.

Several secondary traits have been found to be correlated with grain yield. These traits include anthesis-silking interval, senescence rate, number of ears per plant, number of kernels per row (Derera *et al*. 2007; Gasura *et al*, 2014, Badu-Apraku, 2005). However, in PVA maize hybrids, there are no reports of traits that are associated with grain yield. There are several techniques than can be used to study the relationships among traits that include correlation analysis, path analysis, regression analysis and sometime the use of a t-test to compare the group means (Singh and Chaudhary, 1979). Correlation refers to the association of variables that exhibit some related trends of change. The coefficient of correlation signifies the intensity of correlation between cause and effect (Singh and Chaudhary, 1979). Correlation can be phenotypic as well as genotypic, which expresses the degree to which two characteristics are genetically associated (Singh and Chaudhary, 1979). Both genotypic and phenotypic correlation can be used as the basis of indirect selection (Singh and Chaudhary, 1979).

2.9 Summary

Maize is the preferred staple food in sub-Saharan Africa. However, ordinary white maize has low vitamin A content and thus leading to vitamin A deficiency in rural populations. The consequences of VAD are reduced immune systems, retarded growth, and night blindness and reduced productivity. Pregnant women and lactating mothers are highly affected by these conditions. Bio-fortification of some staple crops has been the recent trend towards combating malnutrition problems such as VAD. In this regard, efforts have been made to develop and deploy orange maize in rural communities. However, when a new technology is introduced, resistance in adoption is always found. Consumer acceptability studies have been widely used to predict the adoption of given technologies. Normally, consumers become accustomed to the taste, physical appearance and other factors that can make them more rigid to accept new products. However, through education and awareness campaigns, it has been shown that the adoption rates of new products such as orange maize would greatly improve.

In breeding orange maize, a bio-fortified crop, there is need to understand the mechanisms of gene action governing some traits. In this study, the combining ability approach was used to understand the gene action governing important traits in maize. Furthermore, the combining ability approach was also used to identify desirable parents based on their general combining ability effects and the desired hybrids based on the specific combining ability effects and *per se* performance. Identification of good parents and hybrids requires the use of desirable testers. Testers are chosen based on the genetic distance from other lines in order to achieve heterosis. In this study, the orange inbred lines were not only crossed to orange but also to QPM and normal maize inbred lines in an attempt to increase heterosis. Furthermore, testers must be highly stable, lack in one of a few traits to allow selection of desirable inbred lines.

When new hybrids are developed, they require to be tested in multi-locations over many years. This allows the agronomic performance, especially grain yield and stability, to be assessed in comparison to the common checks on the market. The additive main effect and the multiplicative interaction model and the genotype plus genotype by environment interaction models have been widely used in analysing multi-environmental trial data. Both models can identify high yielding and stable genotypes, adapted genotypes and can be used to understand the properties of the test locations.

The use of secondary traits to aid or replace the primary trait in selection has been widely used. When a secondary trait is highly correlated with a primary trait, and when its heritability is high, it becomes an ideal candidate that can be used to improve the efficiency of selection. The selection efficiency is improved because selection will be done on a much easier to score trait and requiring less resources for evaluation especially in terms of time and number of replications. High grain yield is desirable in orange maize, however, traits that are highly correlated to grain yield in PVA maize were not known.

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Chapter 3 : ACCEPTABILITY

Is there value for cultivation and use of fresh pro-vitamin A bio-fortified maize in KwaZulu Natal Province, South Africa?

Abstract

Maize is a leading staple in sub-Saharan Africa (SSA) where vitamin A deficiency (VAD) is prevalent. Consequently, pro-vitamin A bio-fortified (PVA) maize has been developed to address VAD in SSA. Unfortunately, food products made with dried PVA maize grain have been found less acceptable relative to their white maize counterparts due to unfamiliar sensory properties. The consumer acceptability of fresh PVA maize has not been investigated, yet in SSA, maize is also traditionally consumed in this form. The aim of this study was to determine the sensory and agronomic acceptability of fresh PVA maize to rural smallholder maize producers and consumers in South Africa. Sensory evaluation and focus group discussions were done using 64 participants. Overall, fresh roasted and boiled PVA maize was preferred over the corresponding white maize forms. The youth showed a higher acceptance of PVA than elders. The farmers showed concerns about and/or interest in PVA maize with regard to its agronomic adaptability, economic value, and food value in terms of processing, sensory, nutritional and health-promoting properties. Thus, there is good potential for PVA maize in its fresh form for utilisation as a food and cash crop in South Africa.

3.1 Introduction

Maize (*Zea mays* L.) is a leading traditional staple food with consumption exceeding 100 kg capita^{-1} year^{-1} in sub-Saharan Africa (Del Ninno *et al*., 2007). South Africa is the largest producer of maize in Africa (Folberth *et al*., 2012). A significant contribution to this produce comes from the resource poor farmers in rural areas, where maize is mainly grown for household consumption (Baiphethi and Jacobs, 2009). Maize in its fresh, dry or processed form makes part of any meal of the day for most rural households in sub-Saharan Africa (Shiferaw *et al*., 2011; Nuss and Tanumihardjo, 2011). Thus, the diet of farmers in rural areas is dominated by starchy foods that are deficient in proteins and vitamins (Akinrele and Edwards, 1971). Consequently, the vulnerable groups, mainly women and children, experience serious nutrient deficiencies, including vitamin A deficiency (VAD) (West Jr and Darnton-Hill, 2008; Wilson *et al*., 1953).

The VAD is associated with several health conditions, including low immunity, physiological disorders and night blindness (Wilson *et al*., 1953; Dowling and Wald, 1958). Several strategies have been introduced to address VAD in sub-Saharan African countries, for example in South Africa, vitamin A supplementation, industrial fortification and promotion of dietary diversification (Coutsoudis *et al*., 1999). Overall, the strategies implemented thus far have not been effective in combating VAD due to various reasons. For example, in South Africa, the vitamin A supplementation programme has limited access to rural communities and industrial fortification does not benefit large populations living in rural areas because they largely produce and process their own food (Faber and Wenhold, 2007). In South Africa, the incidence of VAD increased by 31% in the period from 1994 to 2005 (Nojilana *et al*., 2007). Although the recent South African National Health and Nutrition Examination Survey (SANHANES) indicated modest success in addressing VAD, the national prevalence of VAD was found to be 43.6% for children under the age of five years, indicating a severe public health problem (Shisana *et al.*, 2013).

The HarvestPlus Global Challenge Programme is a recently developed agriculture-based strategy for addressing malnutrition in developing regions through bio-fortification of staple crops (Pfeiffer and McClafferty, 2007). Bio-fortification is the improvement of staple crops to increase the concentration of targeted nutrients through traditional breeding and modern biotechnology (Harjes *et al*., 2008; Ortiz-Monasterio *et al*., 2007). Maize, a major staple crop in Southern Africa has been targeted for bio-fortification by traditional breeding to address VAD in this region (Pfeiffer and McClafferty, 2007; Faber and Wenhold, 2007). Bio-fortification of maize would be a cost effective and sustainable strategy to combat VAD because the bio-fortified maize would be readily available and accessible to the rural poor communities as they would produce it themselves.

The bio-fortification of maize grain with pro-vitamin A to produce pro-vitamin A bio-fortified (PVA) maize changes its sensory properties, including colour, aroma and flavour (Stevens and Winter-Nelson, 2008; Pillay *et al*., 2011) and probably some agronomic traits. Several studies conducted in sub-Saharan African countries, including South Africa, have found a low preference of PVA maize compared to white maize (Stevens and Winter-Nelson, 2008; Pillay *et al*., 2011; Muzhingi *et al*., 2008). Studies on consumer acceptability of PVA maize used foods made with dry grain yet in most parts of sub-Saharan Africa, including Southern Africa, it is part of the tradition and indigenous knowledge system (IKS) to process and consume fresh forms of the maize grain. Rural smallholder farmers generate household livelihoods by selling fresh roasted and boiled maize in local informal markets. The farmers also sell the fresh raw maize cobs to middle men who in turn supply the maize to formal and informal urban markets. The fresh pro-vitamin A bio-fortified maize, if acceptable to consumers, could be an alternative livelihood option for the rural households who are highly depended on agriculture for their livelihoods. Further, the consumption of the fresh bio-fortified maize would enhance food and nutrition security of the poor-resourced households. The aim of this study was to assess the consumer acceptability of fresh boiled and roasted PVA maize to rural smallholder farmers/consumers in KwaZulu-Natal province of South Africa as well as the perceptions of the farmers about adopting PVA maize as a food and cash crop.

3.2 Methodology

3.2.1 Research method

A triangulation approach (Hussein, 2009) was employed using a sensory evaluation test (a pictorial 5 point hedonic scale) complemented by participatory rural appraisal through focus group discussions (FGDs) to explore consumer acceptability of fresh PVA maize. Borrego *et al*. (2009) emphasised the need to use various methodologies and techniques in a way that offers the best chance to obtain useful answers. The triangulation approach was used in this study to improve the reliability of the results obtained.

3.2.2 Study site

The study was conducted in Jozini, a rural area in uMkhanyakude District of KwaZulu-Natal Province, South Africa. It is situated on the Makhathini flats of Maputaland along the Pongola River, 100 km east of Pongola town, 45 km from Sodwana Bay and 150 km from Kosi Bay. Around the study area there is an irrigation scheme comprising of 4 570 ha of irrigable land. The area is dominated by the production of maize, sugarcane, cotton, vegetables and mangoes.

3.2.3 Study participants selection

A purposive sample of 64 maize farmers (also regarded as consumers) from Mjindi, Ndumo and Tugela Ferry irrigation schemes in Jozini participated in this study. The 64 farmers were split into six sensory evaluation and focus group discussion groups. Two of the groups had 10 people whilst the other four groups had 11 people.

3.2.4 Maize varieties and experimental set up

Two maize varieties were used in this study. One variety, HP326-2, was PVA maize whilst the other, SC701, was white. The white variety was used as a control. The two varieties were planted at Makhathini Research Station (27^0S, 32^0E, and 77 m above sea level) during the first week of March 2013. This is the time when most farmers plant for the fresh maize market in the area. Each maize variety was planted in 20 rows of 5 m length with an in-row and inter-row spacing of 0.3 m and 0.9 m, respectively. At planting, 250 kg/ha of magnesium ammonium phosphate (MAP) were applied as a basal fertilizer while top dressing with 250kg/ha of lime ammonium nitrate (LAN) were applied at four weeks after crop emergence. Atrazine, Alachlor and metalochlor were applied as pre-emergence herbicides. After crop emergence, hand weeding was done to keep the field weed free. The planted field was irrigated for three hours once a week from planting to the reproductive stage and thereafter irrigated for three hours twice a week.

3.2.5 Preparation of fresh roasted and boiled maize samples

A total of 256 samples of maize cobs (128 PVA and 128 white) were harvested on the day of evaluation. Cobs of each maize variety were divided into two sub-samples. One sub-sample was boiled while the other was roasted. The maize samples were processed according to the traditional practices of the Zulu tribe in Jozini. One sub-sample of the maize cobs was boiled for two hours by four experienced women who served as research assistants whilst roasting was done on fire by four experienced men who also served as research assistants.

3.2.6 Sensory evaluation

Roasted and boiled samples of both PVA and white maize cobs were blind-labelled with three-digit codes obtained from a Table of Random Numbers. The maize samples were served immediately to the consumer panel in a randomised order determined using a Table of Random Permutations of Nine. Four coded samples of boiled and roasted PVA and white maize cobs were presented to each panellist. Each sample was rated for acceptability based on colour, aroma and taste using a 5-point pictorial hedonic scale, where, 1 = like very much, 2= like, 3= neither like nor dislike, 4= dislike and 5 = dislike very much.

3.2.7 Focus group discussions

Focus group discussions (FGDs) were conducted immediately after sensory evaluation. The intention was to gain deeper insight of consumer perceptions about the use of PVA maize food as well as its suitability as a cash crop. A trained facilitator conducted the discussions in *isiZulu*, the predominant local language in the study site. A set of five guiding questions was used for the FGD. However, the FGDs members were allowed to raise other issues or questions during the discussion sessions. The research questions included the following: What is the value for cultivating PVA yellow maize? What is the value for use of PVA maize? Is it profitable to grow PVA maize? Does it have marketable traits which are comparable to currently grown white maize?

3.2.8 Ethics approval

Ethics approval to carry out the study was obtained from the Humanities and Social Sciences Ethics Committee of the University of KwaZulu-Natal. All farmers signed a written consent to participate in the study. This was complemented by an oral consent from the farmers before each focus group discussion session.

3.3 Statistical analysis

The Statistical Package for Social Science (SPSS) version 15.0 (SPSS, Chicago, III, USA) was used to analyse the data. Both descriptive and inferential statistics techniques were used. The Chi-square test was used to test for relationships between consumer gender and sensory acceptability, and between consumer age and sensory acceptability of the roasted and boiled PVA maize. Recorded FGDs were transcribed to isiZulu text and the English text using two persons who were proficient in both isiZulu and English. The English version of the FGDs transcripts were analysed by Content Analysis, whereby emerging themes and concepts were identified to illustrate the consumer perceptions about PVA maize.

3.4 Results and discussion

3.4.1 Demographic information of the participants

The gender ratio of the study participants followed the usual pattern of females (81%) dominating males (19%) in the smallholder farming system (Table 3.1). This phenomenon is common in most African agricultural system (Gawaya, 2008; Mapiye and Sibanda, 2005; Wells and Gradwell, 2001). Furthermore, maize is considered a women’s crop (Nuss and Tanumihardjo, 2010), which the society perceive as crucial to every woman to cater for the family food security. In some cases, most men leave the rural areas to seek employment in the towns thus leaving fewer men involved in agriculture. Most farmers (64%) were in the 36-60 year age group. This is expected since the younger people (18-35 years) will be in schools, colleges or seeking employment elsewhere, while relatively few older people (61-75 years) are involved in agriculture because of sickness or due to their non-existence given the low life expectancy in most African countries (Bor *et al*., 2013; Mathers *et al*., 2001).

Table 3.1. Gender and age distribution of the study participants

Gender	**N* (%)**	**Age**	**N* (%)**
Female	52 (81%)	18-35	9 (14%)
Male	12 (19%)	36-60	41 (64%)
		61-75	14 (22%)

*N=64

3.4.2 Acceptability of fresh pro-vitamin A maize and relationship of acceptability with gender

In order to have a bigger and clearer picture of the results, the 5-point hedonic rating scale was transformed to a 3-point scale, 1= bad; 2= neutral; and 3= good. This was done by combining the 1 and 2 ratings of the 5-point rating scale and assigning them as 1= bad in the 3-point rating scale, the 4 and 5 ratings of the 5-point scale were combined and assigned 3= good, whilst the 3 rating was transformed to 2 in the new scale (Tables 3.2 and 3.3). Tables 3.2 and 3.3 show that, overall, the study participants preferred the fresh forms of PVA over the fresh white maize counterparts. A high proportion of males (76%) preferred roasted PVA maize, whilst a high proportion of females (79%) preferred boiled PVA maize over the corresponding white maize forms (Table 3.2). Interestingly, overall, the youth (18-35 years) had a higher acceptance of PVA maize compared to the adults (36-60 years) and the elderly (61-75 yrs) (Table 3.3).

Table 3.2 Relationship between acceptability of fresh pro-vitamin A maize forms and consumer gender

Sample / Liking	Boiled fresh PVA maize		*P value	Boiled fresh white maize		*P value	Roasted fresh PVA maize		*P value	Roasted fresh white		*P value
	Gender			Gender			Gender			Gender		
	Female n %)	Male n (%)		Female n (%)	Male n (%)		Female n (%)	Male n (%)		Female n (%)	Male n (%)	
Overall liking			**0.61**			**0.28**			**0.57**	32 (61.5)	9 (75)	**0.08**
Good	42 (80.8)	9 (75.0)		38 (73.1)	11(91.7)		38 (73.1)	8 (66.7)		8 (15.4)	0 (0)	
Neutral	6 (11.5)	1 (8.3)		5(9.6)	1(8.3)		7 (13.5)	3 (25.0)		12 (23.1)	3 (25.0)	
Bad	4 (7.7)	2 (16.7)		9(17.3)	0(0)		7 (13.5)	1 (8.3)				
Taste			**0.04**			**0.06**			**0.59**	29 (55.8)	8 (66.7)	**0.78**
Good	41 (78.8)	7 (58.3)		33(63.5)	11(91.7)		42 (80.8)	11 (91.7)		6 (11.5)	1 (8.3)	
Neutral	2 (3.8)	3 (25.0)		2(3.8)	1(8.3)		3 (5.8)	0 (0)		17 (32.7)	3 (25.0)	
Bad	9 (17.3)	2 (16.7)		17(32.7)	0(0)		7 (13.5)	1(8.3)				
Aroma			**0.62**			**0.39**			**0.57**	28 (53.8)	9 (75.0)	**0.40**
Good	38 (73.1)	10 (83)		35(67.3)	10 (83.3)		38 (73.1)	10 (83.3)		8 (15.4)	1 (8.3)	
Neutral	3 (5.8)	0 (0)		6(11.5)	0(0)		4 (7.7)	0 (0)		16 (30.8)	2 (16.7)	
Bad	11 (21.2)	2 (16.7)		11(21.2)	2(16.7)		10 (19.2)	2 (16.7)				
Colour			**0.86**			**0.46**			**0.42**	37 (71.2)	10 (83.3)	**0.58**
Good	38 (73.1)	9 (75.0)		42(80.8)	11(97.7)		35 (67.3)	7 (58.3)		3 (5.8)	0 (0)	
Neutral	7 (13.5)	2 (16.7)		6 (11.5)	0(0)		9 (17.3)	4 (33.3)		12 (23.1)	2 (16.7)	
Bad	7 (13.5)	1 (8.3)		4(7.7)	1(8.3)		8 (15.4)	1 (8.3)		32 (61.5)	9 (75)	

*P values generated using the Chi-Square test

Table 3.3 Relationship between acceptability of fresh pro-vitamin A maize forms and age of the consumer

Sample / Liking	Boiled fresh PVA maize			*P value	Boiled fresh white maize			*P value	Roasted fresh PVA maize			*P value	Roasted fresh white maize			*P value
	18-35 yrs	36-60 yrs	61-75 yrs		18-35 yrs	36-60 yrs	61-75 yrs		18-35 yrs	36-60 yrs	61-75 yrs		18-35 yrs	36-60 yrs	61-75 yrs	
Overall liking				**0.84**				**0.75**				**0.13**				**0.12**
Good	8[Ŧ] (88.9)[¶]	32 (78.0)	11 (78.6)		6 (66.7)	28 (68.3)	12 (85.7)		6 (66.7)	30 (73.2)	13 (92.9)		6 (66.7)	24 (58.5)	11 (78.6)	
Neutral	0(0)	5 (12.5)	2 (14.3)		2 (22.2)	7 (17.1)	1 (7.1)		0(0)	6(14.6)	0(0)		0 (0)	6 (14.6)	2 (14.3)	
Bad	1 (11.1)	4 (9.8)	1 (7.1)		1 (11.1)	6 (14.6)	1 (7.1)		3(33)	5(12.2)	1(7.1)		2 (22.2)	11 (26.8)	1 (7.1)	
Taste				**0.28**				**0.76**				**0.05**				**0.44**
Good	6 (66.7)	31 (75.6)	11 (78.6)		8 (88.9)	33 (80.5)	12 (85.7)		5(55.6)	25 (61.0)	14 (100)		4 (44.4)	24 (58.5)	9 (64.3)	
Neutral	0 (0)	5 (12.2)	0(0)		0 (0)	3 (7.3)	0 (0)		0(0)	3(7.3)	0(0)		0(0)	5 (12.2)	2 (14.3)	
Bad	3 (33.3)	5 (12.2)	3 (21.4)		1(11.1)	5 (12.2)	2 (14.3)		4(44.4)	13 (31.7)	0(0)		5 (55.6)	12 (29.3)	3 (21.4)	
Aroma				**0.95**				**0.12**				**0.33**				**0.19**
Good	77 (77.8)	31 (75.6)	10 (71.4)		7 (77.8)	27 (65.9)	14 (100)		6(66.7)	26(63.4)	13 (92.9)		6 (66.7)	21 (51.2)	10 (71.4)	
Neutral	0(0)	2 (4.9)	1 (7.1)		0(0)	4 (9.8)	0(0)		1(11.1)	5(12.2)	0(0)		0(0)	9 (22.0)	0(0)	
Bad	2 (22.2)	8 (19.5)	3 (21.4)		2(22.2)	10 (24.4)	0(0)		2(22.2)	10(24.4)	1 (7.1)		3 (33.3)	11 (26.8)	4 (28.6)	
Colour				**0.62**	5 (55.6)	26 (63.4)	11 (78.6)	**0.67**				**0.25**				**0.13**
Good	8 (88.9)	29 (70.7)	10 (71.4)		3 (33.3)	8 (19.5)	2 (14.3)		8 (88.9)	31 (75.6)	14(100)		5 (55.6)	29 (70.7)	13 (92.9)	
Neutral	0(0)	6 (14.6)	3 (21.4)		1 (11.1)	7 (17.1)	1 (7.1)		1(11.1)	5 (12.2)	0(0)		0(0)	2 (4.9)	1 (7.1)	
Bad	1 (11.1)	6 (14.6)	1 (.1)		6 (66.7)	28 (68.3)	12 (85.7)		0 (0)	5(12.2)	0(0)		4 (44.4)	10 (24.4)	0 (0)	

*P values generated using the Chi-Square test, [Ŧ] N; [¶]%

The current findings showing variations in preferences of PVA maize and white maize across consumer age groups and gender have been reported in previous studies (Nuss *et al*., 2012). For example, Pillay (2011) reported that the acceptability of PVA maize food products, phuthu, samp and soft porridge, decreased as the age of the consumer increased. The authors attributed the findings to the fact that older consumers had become more accustomed to white maize than younger consumers. The same suggestion could be applicable to the findings of this study.

The FGDs indicated similar results as those of sensory evaluation and revealed the possible reasons. For the young age group, fresh PVA maize consumption was a new experience. The adults and elderly groups (especially above 45 years) were more familiar with fresh PVA maize consumption. The older generation referred to PVA maize as 'drought food' while the younger generation (under 45 years) regarded it as 'olden days food'. The consumers older than 45 years related the sensory evaluation to their past experience with yellow maize consumption. This is the group that experienced drought in 1983 in KwaZulu-Natal. This experience was used as a reference when discussing yellow maize: "*It was not nice because I had a stomach ache (isisusegazi) when I ate this maize; it was not good for my stomach; it is not in the market you only find it during drought times".* As stated in the literature perception is the process by which physical sensations are selected, organized and interpreted (Walter et., al 1989). It is an event over time, therefore beyond perception, interpretation of previous experience with food that acts as a decisive factor in getting meaning. Many consumers are usually subjected to perception distortions caused by the events around the first experience with the food determining their future responses. In this study the findings reveal an opportunity for the acceptability of PVA since the younger generation (future consumers) does not hold any negative attitude or misperceptions about PVA maize.

3.4.3 Consumer perceptions and concerns about pro-vitamin A maize

The FGDs findings on the perceptions and concerns of consumer/farmers about PVA maize are presented in Table 3.4. The farmers perceived yellow/orange PVA maize as feed rather than food. This was based on their traditional practices of producing white maize for household use as food, while yellow maize is traditionally used mainly as chicken feed. Some farmers stated that the PVA maize was good for feeding chickens. According to the farmers, PVA maize enhanced the fertility of chickens and that was of concern as they thought that the fertility-enhancing properties of the PVA maize would be also imparted to humans if they consumed the maize and would disrupt their contraception methods.

Table 3.4 Concerns of farmers towards pro-vitamin A maize

Theme	Concept	Issues discussed
Adaptability under local conditions	Resistance to heat drought	Farmers wanted PVA maize that can tolerate heat and drought. Breeding programs are required to develop varieties with heat and drought stress tolerance.
Marketability	Suitability of agronomic traits	Farmers wanted high yielding maize with huge cobs and large kernel sizes and an extended shelf life as comparable to white maize. This raises need to develop PVA maize cultivars with better agronomic traits.
Processing	Palatability	Farmers mentioned that special foods such as corn steamed bread and African beer were more flavour-some compared to white maize. This poses a challenge to food and consumer scientists to generate better food products that could mask unfamiliar taste of PVA maize.
Profitability	Quality and pricing	The farmers were worried that planting yellow maize close to white maize would cause contamination due to cross-pollination thus reducing the quality and aesthetic value of white maize. These would eventually reduce the market price of white maize on the nearby fields. In South Africa yellow kernels in white maize reduces market grade (Kruger *et al*. 2009).
Value for use	Nutritional and health benefits	Farmers wanted to know the nutritional benefits of PVA maize. Thus, the nutritional and health benefit of PVA should be emphasized during promotion, because this can be used to differentiate PVA and white maize.

Despite the negative perceptions about the yellow/orange kennel colour, the farmers valued the nutritional benefit of PVA maize and perceived it as 'healthy'. This was after the facilitator explained the bio-fortification process as it was an unfamiliar concept to the farmers. The farmers indicated that, whilst they appreciated and valued the nutritional properties of the PVA maize, they were concerned that, because of their invisibility, the health properties of the maize would be likely not considered by the consumers as they normally used physical attributes as indicators of maize quality. In this regard, the size of the maize cob, kernel size, hardness and colour are the most used quality attributes when selecting maize. Consequently, the farmers suggested that communities be educated about the health-beneficial properties of PVA maize. The farmers further pointed out that the agronomic traits of PVA maize, cost of production, ability to withstand environmental factors, marketability and usability of PVA bio-fortified maize were key determinants of its acceptability (Table 3.4).

3.4.4 Eagerness of farmers to produce and sell fresh pro-vitamin A maize

Regardless of the concerns mentioned, the participants showed marked enthusiasm to accept PVA maize for household agricultural production and profit-making through selling to livestock owners. In this regard, farmers made recommendations on how to accelerate the process of promotion of PVA maize (Table 3.5).

Table 3.5 Action plan proposed by the farmers to promote pro-vitamin A maize

Themes	**What should be done**	**By who**
Convincing agricultural officials	• Extension officers to take an active role in providing seeds to farmers • Extension officers to organise demonstrations	Department of Agriculture and Environmental Affairs
Capacity building	• Training on production and management of PVA maize	Researchers and extension officers
Communication	• Community leaders and farmers associations must sensitise farmers and community members about PVA and its benefits	Extension officers

3.5 Conclusions

Overall, the farmers and consumers preferred fresh PVA maize either in boiled or roasted form over the corresponding white maize forms. Females preferred the boiled form of the PVA maize whilst the males preferred the roasted form. The youth were more optimistic about PVA maize, whilst the elders (above 60 years) had a slightly higher preference for the fresh white maize forms compared to the corresponding PVA maize forms. Farmers showed concerns over PVA maize in areas that include adaptability to the local environment, marketability, processing and palatability qualities, profitability, and nutritional and health benefits. Despite these concerns, farmers suggested a holistic multi-stakeholder approach to raise awareness and educate farmers about PVA maize, a strong indicator of the good potential for the adoption and utilisation of the fresh PVA maize.

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Chapter 4 : ADAPTABILITY

Evaluation of grain yield and related agronomic traits of hybrids derived from pro-vitamin A maize inbred lines in multi locations

Abstract

Cross-over genotype by environment interaction (GEI) is the major impediment in variety recommendation in many crops including maize. In this study, a set of hybrids were generated using the orange maize inbred lines and were evaluated together with the commercial checks in a set of lowland and upland environments . However, when GEI is present and is of crossover type, variety recommendation must be based on mean yield and stability. When the GEI pattern is repeatable across years, then the environments must be subdivided into mega-environments in which the extent of GEI is reduced in each mega-environment. The objectives of this study were to assess the nature of GEI and to identify stable and high yielding varieties among a set of hybrids derived using the orange maize inbred lines. Analysis of variance showed that GEI was significant and was second in importance after environment source of variation. Some genotypes such as 14PVAH-106 (54) and 14PVAH-120 (61) yielded better than the checks in most sites. The genotype comparison bi-plot showed that these genotypes were more stable and high yielding cross environments. The hybrids are ideal products to target the farmers and consumers who showed preference for PVA over white maize in South Africa. The high yielding and stability of these hybrids were associated with longer ear length, high shelling percentage, near zero anthesis-silking intervals and resistance to diseases and lodging.

4.1 Introduction

Multi-environmental trial analyses are a routine component of a plant breeding pipeline (Gauch, 2013). Every year, new varieties are developed, and they have to be tested for their agronomic performance in diverse agro-ecological regions before release. Heterosis is thus expected to be maximum given that diverse lines were used. These hybrids were then tested for their performance against commercial hybrids in major maize producing regions in South Africa. However, when genotypes are evaluated in multi-locations, genotype by environment interaction is inevitable (Yan and Tinker, 2006; Gauch, 2013). Genotype by environment interaction (GEI) is the differential performance of genotypes grown in different sets of environments. Environments normally show temporal and spatial variations in factors that include biotic stresses, climatic conditions (temperature and rainfall patterns) and soil characteristics (Gasura *et al*., 2015). This results in differential performance of the genotypes across different locations, an occurrence known as crossover GEI (Finlay and Wilkinson, 1963). A stable variety must be capable of utilizing the resources available in a better environment (high potential), and maintain above average yield in other locations, a situation known as dynamic concept of stability (Yan and Kang, 2002).

Visualization of GEI pattern is very important in variety development and recommendation (Yan and Kang, 2002). Cluster analysis (Bernardo, 2002) and the use of biplots has allowed visualization of GE patterns in a graphical approach created from the two-way data set (Yan and Kang, 2002; Yan and Tinker, 2006). The additive main effect and multiplicative interaction (AMMI) biplot (Gauch, 2013) and the genotype main effect plus GEI (GGE) biplot (Yan and Tinker, 2006) have been used widely to display the GE patterns graphically. The strengths and weaknesses of each model have been highly debated (Gauch et al., 2008; Yang et al., 2009). The AMMI model has an advantage in model diagnostic, because it has an in-built post-dictive Gollob F-test (Zobel *et al*., 1988). However, it can only handle balanced data sets from randomized complete block designs. The GGE bi-plots have an advantage of using adjusted mean values that can be obtained from any design such as the un-balanced analysis of variance. The GEI two-way data is subjected to different approaches of singular value partitioning (SVP) (Yan and Tinker, 2006). The biplot model that is fitted to residuals after the removal of the environmental main effect (environment centred bi-plot) is called a GGE bi-plot or site regression (SREG) bi-plot (Yang *et al*., 2009). A GGE bi-plot generated based on the SREG model has proven to be useful in grouping similar environments, identifying ideal testing sites, understanding the correlation of traits with either locations or genotypes and in identifying stable genotypes with high yield (Yan and Kang, 2002; Yan and Tinker, 2006) and this technique has been widely used (Gasura *et al*., 2015; Setimela *et al*., 2017a,b). The objectives of this study were to; 1) determine the importance and magnitude of GE and 2) identify stable and high yielding orange maize hybrids to recommend for release.

4.2 Materials and methods

4.2.1 Plant materials

A set of 20 (PVA, maize) lines (Table 4.1) were planted at Makhathini (77m Altitude; Latitude 27.39^{0}S; Longitude 32.17^{0}E), and Ukulinga Research Farms (Latitude 29°.66’S 30°, Longitude, 40'E) during the 2012/2013 summer season. Staggered planting of the lines were employed to synchronize flowering. This entailed three planting dates at a weekly interval. The 20 lines were crossed using a 10 x 10 North Carolina design II mating scheme to generate 100 single cross hybrids. The 100 single cross hybrids generated were evaluated together with two widely grown commercial hybrids, PAN6Q308 and DKC80-40BRGEN and three (11C1483, 11C1774 and 11C1579) white fresh maize hybrids from advanced trials previously conducted at the University of KwaZulu Natal South Africa. The total hybrids used were 105.

Table 4.1 Main features of 20 maize inbred lines used in developing hybrids

Entry	pedigree	Parent type		Grain type	Characteristics
1	12UK15-13	Line	female	PVA	Long ear, slight lodging, prolific
2	12UK15-10	Line	female	PVA	Long ear, good standing ability
3	12UK15-15	Line	female	PVA	Very prolific, good standing ability, high yield
4	12UK15-18	Line	female	PVA	Long ear, good standing ability
5	12UK15-21	Line	female	PVA	Long ear, susceptible to lodging
6	12UK15-32	Line	female	PVA	High seed yield, good standing ability
7	12UK15-33	Line	female	PVA	Long ear, susceptible to lodging
8	12UK15-36	Line	female	PVA	High seed yield, good standing ability
9	12UK15-58	Line	female	PVA	Very long ear, good standing ability, good yield
10	12UK15-60	Line	female	PVA	Long ear, good standing ability
11	12CR3-7	Tester	Male	PVA	CIMMYT line, long ear, high yield and high vitamin A
12	12CR3-8	Tester	Male	PVA	CIMMYT line, long ear
13	12CR3-9	Tester	Male	PVA	CIMMYT line, short ear
14	12CR3-22	Tester	Male	QPM	QPM, medium ear, yellow
15	12CR3-25	Tester	Male	QPM	QPM, medium ear, yellow
16	12CR3-26	Tester	Male	QPM	QPM, long ear, yellow
17	12UK20-7	Tester	Male	NM	High yield, prolific, yellow normal maize (non PVA and QPM)
18	12UK40-14	Tester	Male	NM	High yield, prolific, yellow normal maize (non PVA and QPM)
19	12UK20-12	Tester	Male	NM	High yield, prolific, yellow normal maize (non PVA and QPM)
20	12UK16-14	Tester	Male	NM	Temperate, high yield potential, yellow

CIMMYT-International Maize and Wheat Improvement Center, NM-Normal Maize, PVA-pro-vitamin A maize inbred lines, QPM-quality protein maize inbred line.

4.2.2 Description of trial sites

Hybrids were evaluated at four sites (Cedara, Dundee, Jozini, and Ukulinga). The geographical descriptions of the sites are given in Table 4.2. The soil in the testing field of Ukulinga Research Farm is sandy clay-loam, fertile and friable with good water drainage (Cambisol). It is composed of 35% sand, 44% silt, 21% clay, 7.4 pH, 1.2% organic matter, 10.32 ppm available phosphorous (P), and cation exchange capacity (CEC) of 22.34 (meq/100 g). However, it is susceptible to cracking and crusting under flooding. Cedara Research Station is characterised by sandy clay soils which are reasonably fertile and well drained. Chances of flooding are very low due to a good slope and ground cover. The fields at Ukulinga and Dundee were ploughed and disked before planting while minimum tillage was done at Cedara. The Cedara field had high organic matter from the stover of preceding maize crop. The ground cover also provided mulch and helped in moisture conservation.

Table 4.2 Geographical coordinates and environmental conditions for the study sites

Sites	Latitude	Longitude	Altitude (metres above sea level)	Total annual rainfall (mm)	Temperature range (ºC)
Cedara	29°.54’S	30°.26’E	1068	696.96	9.85 – 24.41
Dundee	28°.13’S	30°.31’E	1219	782.80	9.70 – 24.10
Jozini	27°.39’S	32°.10’E	77	428	-16- 30
Ukulinga	29°.66’S	30°.40'E	809	676.17	13.65 – 24.83

4.2.3 Experimental design and trial management

The 105 hybrids were evaluated across four sites (Table 4.1) in KwaZulu-Natal province of South Africa, during the 2013/14 summer cropping season. Two boarder rows were planted at the ends, around the experimental sites. All experiments were laid out as incomplete block designs consisting of a21 x 5 α-lattice design with four replications at all the sites. Each plot consisted of two rows of 5 m length. Plants were spaced at 30cm within rows and 90 cm between rows, giving a total of 32 plants per plot. A total of 250 kg/ha NPK (56N: 83P: 111K) compound fertilizer was applied as basal dressing during planting, immediately after planting curator was applied around the experimental site to repel rodents. The fields were irrigated to establish the crop. Six weeks after planting, 250 kg/ha of lime ammonium nitrate (LAN 28% N) was applied as a top dressing. Weed control was achieved through both chemical such as Basagran (to kill nutsedge), Gramoxone (all fresh weeds) and Troopers (broadleaf weeds including morning glory) and hand weeding, and all sites were rainfed until hand harvesting after physiological maturity.

4.3 Data collection

Data was collected following the standard protocols which are used at International Maize and Wheat Improvement Center (CIMMYT). Grain yield was measured as grain mass per plot adjusted to 12.5% grain moisture content at harvest. Ear prolificacy (EPP) was measured as the total number of ears per plot divided by the total number of plants per plot. Ear length was measured in cm from the tip of the cob to the base of the cob. Shelling percentage (SP) was measured as the grain weight per ear divided by the ear weight before shelling. Grain moisture content (MOI) was measured as percentage water content of grain measured at harvest. Days to anthesis (AD), number of days after planting when 50% of the plants shed pollen. Days to silking (SD), number of days after planting when 50% of the plants showed silks. Anthesis-silking-interval (ASI) was estimated as SD-AD. Plant height (PH) (cm) was measured as the distance from the base of plant to the insertion point of the top tassel. It was measured when all the plants had flowered, since plants reach their maximum height at flowering. Ear height (EH) (cm) was measured as height from ground level up to the base of the upper most ear. Ear position was measured as the ratio of ear height to plant height. Root lodging (RL) was measured as a percentage of plants that showed lodging by being inclined by up to 45°. Stem lodging (SL) was measured as a percentage of plants that were broken below the ear. TL was measured as the sum of RL and SL. Diseases that include gray leaf spot, turcicum leaf blight, ear rots and phaeosphaeria leaf spot were measured based on a 1-5 scale where 1 is a clean plant where 5 is a severely diseased plant. Ear aspect was measured on a scale of 1 -5 where 1 is excellent and five is bad while grain texture was measured on a scale of 1-5 where 1 is flint while 5 is dent.

4.4 Data analyses

Single site and combined analysis of variance (ANOVA) were done on the data but Cedara was not used in across site ANOVA because its error variance was different from the rest of the sites based on the Bartlett's test. Combined ANOVA was carried out using the following model: $Y_{i(j)(k)l} = b_i(r_j)(s_k) + r_j(s_k) + g_l + s_k + g_l s_k + e_{i(j)(k)l}$, where $Y_{i(j)(k)l}$ is the response of the l^{th} genotype in the i^{th} block nested within the j^{th} replication also nested in the k^{th} site; $b_i(r_j)(s_k)$ is the effect of the i^{th} block within the j^{th} replication also nested within k^{th} site and i = 1,2,3...21; $r_j(s_k)$ is the effect of the j^{th} replication nested within the k^{th} site and j=1,2,3; g_l and s_k are the main effects of genotypes and sites and l=1,2,3…105 while k=1,2,3,4, respectively; $g_l s_k$ is the interaction effect between the l^{th} genotype and the k^{th} site; and finally $e_{i(j)(k)l}$ is the pooled error term. The sites are referred to as environments in this chapter. The genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) were calculated for all quantitative traits, according to Singh and Chaudhary (2004), using the following equations:

$$GCV\ (\%) = \frac{\sqrt{\sigma^2 g}}{x} \text{ x } 100$$

$$PCV\ (\%) = \frac{\sqrt{\sigma^2 p}}{x} \text{ x } 100$$

Where,

$\sigma^2 g$ = genotypic variance,

$\sigma^2 p$ = phenotypic variance and

X= grand mean of the character.

The variance components attributed to locations ($\delta^2 l$), genotypes ($\delta^2 g$), genotypes x location ($\delta^2 gl$), and random error ($\delta^2 e$) were estimated by solving the equations formed by equating the mean squares to their respective expected mean squares. The broad sense coefficients of genetic determination (broad sense heritability based on fixed genotypes) on a single plot basis as: $\delta^2 g/ (\delta^2 g + \delta^2 gl + \delta^2 e)$. The Pearson's correlation coefficients of grain yield and secondary traits were calculated using GenStat software (GenStat, 2014).

The adjusted means of genotypes per environment from ANOVA were subjected to the genotype plus genotype by environment interaction (GGE) comparison biplot analysis using

GenStat software 17th edition (GenStat, 2014). The model for the GGE biplot used was described by Yan and Tinker (2006) and Yan and Kang (2002) as: $Y_{ij} - \mu - \beta_j = {}^{k}\sum_{l=1} \lambda_l \xi_{il} \eta_{jl} + \varepsilon_{ij}$,, where Y_{ij} is the mean yield of the i^{th} genotype in the j^{th} environment; μ is the grand mean; β_j is the main effect of the environment j; λ_l is the singular value of the l^{th} principal component and k =2 in this case; ξ_{il} is the eigen vector of the genotype i for PC l; η_{lj} is the eigen vector of environment j for PC l; and ε_{ij} is the residual associated with genotype i in the environment j. Based on this model the biplot is environment-centered using GenStat software version 17 (GenStat, 2014). Visualization of the mean yield and stability of genotypes using a genotype comparison biplot was achieved by representing an average environment by an arrow. A line that passed through the biplot origin to the average environment was drawn followed by a perpendicular line that passed through the biplot origin.

4.5 Results

4.5.1 Analysis of variance and hybrid performance at Jozini

There were highly significant differences (P<0.001) in grain yield (GY), ears per plant (EPP), ear length (EL), ear position (EPO), anthesis date (AD), silking date (SD) and anthesis-silking interval (ASI) among hybrids evaluated at Jozini (Table 4.3). Ear height was significant at P<0.01, while plant height (PH) and moisture (MOI) were not significantly different. Broad sense heritability ranged from 14 to 55% (Table 4.3). The top 10 performing hybrids were from the PVA group and their yield ranged from 5.93 – 6.78 t/ha (Table 4.4). These hybrids include 14PVAH-9, 14PVAH-7, 14PVAH118 and 14PVAH-106 among others. These hybrids had a 46.9% gain in yield and negative gain in EPO, SD and AD over the checks used. The coefficient of variation (CV) values were low (<20%) for all traits except ASI which had a CV value of 168.83% (Table 4.4).

4.5.2 Analysis of variance and hybrid performance at Ukulinga

At Ukulinga, there were significant differences (P< 0.001) among hybrids for all traits studied except ASI which was non-significant (Table 4.5). Broad sense heritability was very low for grain yield (5.43%) and ranged from 4.04-66.30% for other traits (Table 4.5). All the PVA hybrids were defeated in terms of grain yield by a check hybrid, DKC80-40BRGEN that yielded 8.71 t/ha (Table 4.6). However, some of the PVA hybrids such as 14PVAH-97, 14PVAH-48, 14PVAH-195 and 14PVAH-9 yielded at par (about 7 t/ha) with one of the famous commercial check hybrid, PAN6Q308. The yield gain for the PVA hybrids over the checks was very low (1.22%) and all other traits showed negative gain except ASI that showed a huge positive gain (35%) (Table 4.6).

4.5.3 Analysis of variance and hybrid performance at Dundee

At Dundee, ASI and EPO showed significant difference at P<0.05 while the rest of the traits showed highly significant differences (P<0.001) among hybrids evaluated (Table 4.7). Heritability for grain yield was fairly high (46.39%) and ranged from 7.57 to 56.4 for other traits studied. A commercial hybrid DKC80-40BRGEN, yielded at par with one of the PVA hybrid 14PVAH-165, with 10.62 t/ha and 10.40 t/ha, respectively (LSD = 1.50 t/ha) (Table 4.8). Other check hybrids such as 11C1579, 11C1774 and 11C1483 produced grain yield which was comparable to some PVA hybrids that include 14PVAH-175, 14PVAH-159 and 14PVAH-120 among others (Table 4.8). The yield gain of the top performing PVA hybrids was 10.2% over the best check hybrids (Table 4.8).

4.5.4 Analysis of variance and hybrid performance at Cedara

There were significant differences (P<0.05) among hybrid traits studied at Cedara except EL, SL, TL, ASI and ET that were not significantly different (Table 4.9). Heritability for grain yield was 14.32% (Table 4.9). All commercial checks hybrids had lower yields (6-7 t/h) compared to the PVA hybrids that include 14PVAH-181, 14PVAH-53 and 14PVAH-77 (8-9 t/ha) among others (Table 4.10). The PVA hybrids had a 40.98% more yield than the check hybrids. The CV values were low (<20%) for all traits except GT that had a CV value of 47.74% (Table 4.10).

4.5.5 Analysis of variance and hybrid performance across sites

Across the four sites (Jozini, Dundee, Ukulinga and Cedara) there were highly significant (P<0.001) differences on the site, entry, and genotype by environment interaction means squares for all traits that include GY, EPP, EL, PH, EH, EPO, MOI, ASI, SP, TL, RL, SL, AD and SD (Table 4.11). Heritability for grain yield across sites was medium (41%). The error CV was low (<20%) for all traits but was high for ASI, SL, RL and TL. For grain yield, the genotype by environment interaction variance component was higher than the genotype variance component (0.41 vs 0.14, respectively) (Table 4.11). All check hybrids were inferior in terms of grain yield performance compared to the PVA hybrids (Table 4.12). The top 10 performing PVA hybrids had 18.2% yield advantage over the five commercial hybrids studied. Hybrids 14PVAH-106, 14PVAH-120 and 14PVAH-9 were among the top 10 yielding PVA hybrids (Table 4.12). Some of the hybrids that were listed among the top 10 performers across sites were also found to be among the top 10 performers in specific single sites. For example, 14PVAH-106, 14PVAH-9 and 14PVAH-118 were among the top ranking at Jozini; 14PVAH-120, 14PVAH-159 and 14PVAH-165 were among the top ranking at Dundee; 14PVAH-9 was among the top hybrids at Ukulinga while 14PVAH-77 was among the best at Cedara. Some top yielding hybrids had longer ears, high moisture content, near zero or negative ASI values, high SP and very low ET scores (Table 4.12).

Table 4.3 Mean square values and their significance for hybrid traits studied at Jozini

Source	DF	GY	EPP	EL	PH	EH	EPO	MOI	AD	SD	ASI
Rep	3	1.87	0.014	0.93	866.9**	124.0	0.002	0.17	0.86	2.09	2.58
Rep.Block	36	2.34***	0.050**	6.76***	681.4***	231.4*	0.004***	1.18**	5.15***	6.90***	2.88
NP	1	8.53**	1.748***	4.56	33.8	270.3	0.004	0.06	2.87	1.29	7.99*
Entry	104	1.53***	0.076***	8.60***	508.6	383.3**	0.004***	1.16	11.08***	11.51***	4.59***
Residual	255	0.92	0.029	2.42	170.1	135.5	0.002	0.67	2.04	1.94	2.06
Total	399	1.23	0.047	4.42	310.1	209	0.003	0.83	4.68	4.89	2.81
Mean		5.01	1.079	21.10	261.8	121.2	0.463	0.46	0.46	59.60	0.88
σ^2G		0.15	0.012	1.55	84.6	62.0	0.0005	0.12	2.26	2.39	0.63
σ^2E		0.92	0.029	2.42	170.1	135.5	0.0019	0.66	2.04	1.94	2.06
σ^2P		1.07	0.041	3.97	254.7	197.5	0.0024	0.78	4.30	4.33	2.69
ECV (%)		19.13	15.698	7.38	5.0	9.6	9.2915	175.86	308.62	2.34	171.13
GCV (%)		7.80	10.062	5.89	3.5	6.5	4.8857	74.27	324.81	2.60	94.99
Heritability (%)		14.24	29.120	38.95	33.2	31.4	21.660	15.14	52.55	55.25	23.55

DF-degrees of freedom, GY-grain yield, EPP-ears per plant, EL-ear length, EH-ear height, EPO-ear position, MOI-moisture content, AD-anthesis date, SD-silking date, ASI-anthesis-silking interval, NP-number of plants, σ^2G-genotypic variance component, σ^2E-error variance component, σ^2P-phenotypic variance component, ECV-error coefficient of variation and GCV-genetic coefficient of variation. PH, EPO, AD, SD and ASI had an error DF of 253. *-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 4.4 Mean performance of top 10 hybrids against checks at Jozini

Entry Code	Entry Name	GY	EPP	EL	PH	EH	EPO	MOI	AD	SD	ASI
5	14PVAH-9	6.78	1.30	21.61	282.29	133.80	0.4746	16.68	60.47	60.52	0.046
4	14PVAH-7	6.65	1.19	20.98	278.03	121.10	0.4366	17.19	58.47	59.00	0.528
60	14PVAH-118	6.35	1.05	22.66	294.76	131.25	0.4454	17.64	59.04	60.73	1.695
34	14PVAH-67	6.35	1.02	20.67	274.72	127.67	0.4637	16.42	58.48	58.49	0.019
20	14PVAH-39	6.32	1.21	23.31	270.85	110.99	0.4108	17.39	60.75	61.00	0.246
26	14PVAH-51	6.23	1.06	23.08	256.69	122.48	0.4775	17.06	57.99	58.02	0.030
32	14PVAH-63	6.08	1.10	20.11	276.54	132.26	0.4785	15.59	57.47	58.50	1.030
54	14PVAH-106	5.96	1.15	21.96	276.44	115.92	0.4181	17.06	58.99	60.26	1.270
30	14PVAH-59	5.95	1.01	22.48	268.06	123.39	0.4613	15.74	59.45	59.50	0.048
99	14PVAH-193	5.93	1.30	18.99	263.33	132.58	0.5032	15.53	58.47	58.53	0.061
Mean of top 10 PVA hybrids		6.26	1.14	21.59	274.17	125.14	0.4570	16.63	58.96	59.46	0.497
102	DKC80-40BRGEN	4.85	1.25	16.97	265.35	125.12	0.4716	14.55	57.95	59.03	1.080
105	11C1483	4.74	1.03	21.73	260.53	105.08	0.4034	15.42	59.97	60.02	0.053
104	11C1774	4.50	1.03	19.99	241.45	117.04	0.4835	15.73	58.98	60.02	1.043
103	11C1579	4.13	0.97	21.74	271.45	141.04	0.5201	16.23	62.98	63.01	0.027
101	PAN6Q308	3.08	0.90	20.23	267.90	111.19	0.4139	15.82	62.11	61.91	-0.197
Mean of all checks		4.26	1.04	20.13	261.33	119.90	0.4585	15.55	60.40	60.80	0.401
% Genetic gain of PVA hybrids		46.93	9.93	7.23	4.91	4.38	-0.3298	6.93	-2.38	-2.21	23.972
Grand mean		5.01	1.08	21.10	261.80	121.21	0.4629	16.37	58.76	59.60	0.838
LSD (5%)		1.40	0.25	2.27	19.04	16.94	0.0627	1.19	2.09	2.03	2.093
CV (%)		19.01	15.64	7.37	4.97	9.59	9.3000	4.97	2.43	2.43	168.830

GY-grain yield, EPP-ears per plant, EL-ear length, EH-ear height, EPO-ear position, MOI-moisture content, AD-anthesis date, SD-silking date, ASI-anthesis-silking interval, LSD-least significant difference and CV-coefficient of variation.

Table 4.5 Mean square values and their significance for hybrid traits studied at Ukulinga

Source	DF	GY	EPP	EL	EA	TL	MOI	AD	SD	ASI
Rep	3	1.90	0.03	12.28*	0.25	1239.2*	12.08***	36.06***	45.38***	1.526
Rep.Block	38	3.84***	0.10***	7.52***	4.42***	1175.9***	3.15**	11.12***	13.89***	1.4437*
NP	1	3.10	0.34**	0.12	0.82	800.0	0.09	28.41**	18.34*	1.097
Entry	104	1.92	0.15***	8.29***	3.11***	776.3***	3.28***	23.97***	24.40***	1.028
Residual	253	1.56	0.04	3.59	1.66	335.8	1.62	2.70	3.51	0.880
Total	399	1.88	0.07	5.25	2.29	538.6	2.27	9.36	10.30	0.977
Mean		5.70	1.36	19.18	5.19	77.9	17.43	81.97	81.36	-0.608
σ^2G		0.09	0.03	1.18	0.36	110.1	0.41	5.32	5.22	0.037
σ^2E		1.56	0.04	3.59	1.66	335.8	1.62	2.70	3.51	0.880
σ^2P		1.65	0.07	4.76	2.02	445.9	2.03	8.02	8.74	0.917
ECV (%)		21.90	14.35	9.88	24.80	23.5	7.30	2.01	2.30	-154.16
GCV (%)		5.25	12.38	5.65	11.62	13.5	3.69	2.81	2.81	-31.648
Heritability (%)		5.43	42.68	24.67	17.99	24.7	20.36	66.30	59.79	4.044

DF-degrees of freedom, GY-grain yield, EPP-ears per plant, EL-ear length, EA-ear aspect, TL-total lodging, MOI-moisture content, AD-anthesis date, SD-silking date, ASI-anthesis-silking interval, NP-number of plants, σ^2G-genotypic variance component, σ^2E-error variance component, σ^2P-phenotypic variance component, ECV-error coefficient of variation and GCV-genetic coefficient of variation. EA, MOI, SD and ASI had an error DF of 253. *-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 4.6 Mean performance of top 10 hybrids against checks at Ukulinga

Entry Code	Entry Name	GY	EPP	EL	EA	TL	MOI	AD	SD	ASI
49	14PVAH-97	7.85	1.32	19.98	7.52	62.33	17.65	79.27	79.53	0.26
25	14PVAH-49	7.26	1.33	22.13	5.02	80.15	16.98	84.01	83.00	-1.01
100	14PVAH-195	7.23	1.23	21.33	4.53	58.61	17.66	82.26	81.25	-1.01
5	14PVAH-9	7.11	1.53	19.09	3.76	52.51	17.22	82.51	81.50	-1.01
9	14PVAH-17	6.99	1.60	17.40	5.74	50.89	17.29	76.99	75.99	-0.99
99	14PVAH-193	6.94	1.58	18.33	5.55	98.44	18.09	78.52	77.50	-1.02
58	14PVAH-114	6.93	1.80	18.10	7.01	59.85	18.46	80.99	80.49	-0.51
98	14PVAH-191	6.79	1.52	18.99	5.51	80.57	17.22	81.01	80.01	-1.00
38	14PVAH-75	6.76	1.60	16.92	6.04	75.39	16.84	82.76	81.74	-1.02
69	14PVAH-136	6.69	1.76	18.48	5.69	101.37	17.03	76.00	75.02	-0.98
Mean of top 10 PVA hybrids		7.05	1.53	19.08	5.64	72.01	17.44	80.43	79.60	-0.83
102	DKC80-40BRGEN	8.71	1.68	20.96	7.52	61.26	16.90	81.01	80.00	-1.01
101	PAN6Q308	7.04	1.61	18.57	5.76	76.19	18.63	82.91	82.05	-0.86
104	11C1774	6.77	1.64	17.47	5.95	80.60	19.31	83.48	82.51	-0.97
105	11C1483	6.73	1.77	17.91	5.02	78.91	17.25	82.01	79.50	-2.51
103	11C1579	5.60	1.16	21.08	6.65	90.17	17.18	82.06	80.97	-1.09
Mean of all checks		6.97	1.57	19.20	6.18	77.43	17.85	82.29	81.01	-1.29
% Genetic gain of PVA hybrids		1.22	-2.79	-0.64	-8.76	-6.99	-2.29	-2.26	-1.73	-35.59
Grand mean		5.70	1.36	19.18	5.19	77.90	17.43	81.97	81.36	-0.61
5% LSD		1.82	0.28	2.76	1.87	26.66	1.85	2.39	2.73	1.37
% CV		22.01	14.37	9.88	24.86	23.47	7.32	2.01	2.30	-156.32

GY-grain yield, EPP-ears per plant, EL-ear length, EA-ear aspect, TL-total lodging, MOI-moisture content, AD-anthesis date, SD-silking date, ASI-anthesis-silking interval, LSD-least significant difference and CV-coefficient of variation.

Table 4.7 Mean square values and their significance for hybrid traits studied at Dundee

Source	DF	GY	SP	EPP	EL	PH	EH	EPO	SL	RL	TL
Rep	3	14.86***	8.81	0.12*	1.01	989.5*	17.2	0.004	230.13***	1.01	276.91**
Rep.Block	36	5.47***	12.05*	0.12***	5.42***	1148.3***	795.8***	0.005***	116.57***	5.42***	183.3***
NP	1	214.04***	18.64	0.83***	48.63***	7799***	4503.2***	0.014*	6669.52***	48.63***	11951.56***
Entry	104	4.60***	24.38***	0.26***	9.86***	1034.8***	430.2***	0.003*	84.86***	9.86***	114.52***
Residual	255	1.03	7.08	0.04	1.46	348.20	153.30	0.00	34.31	1.46	55.52
Total	398	3.01	12.10	0.11	4.12	622.90	293.30	0.00	73.01	4.12	113.90
Mean		7.68	83.36	1.47	19.93	267.92	125.97	0.47	14.27	19.93	22.30
σ^2G		0.89	4.33	0.05	2.10	171.65	69.23	0.00	12.64	2.10	14.75
σ^2E		1.03	7.08	0.04	1.46	348.20	153.30	0.00	34.31	1.46	55.52
σ^2P		1.93	11.40	0.09	3.56	519.85	222.53	0.00	46.95	3.56	70.27
ECV (%)		13.22	3.19	13.84	6.07	6.96	9.83	9.92	41.04	6.07	33.41
GCV (%)		12.30	2.50	15.79	7.27	4.89	6.60	2.84	24.91	7.27	17.22
Heritability		46.39	37.95	56.54	58.91	33.02	31.11	7.57	26.92	58.91	20.99

DF-degrees of freedom, GY-grain yield, SP-shelling percentage, EPP-ears per plant, EL-ear length, PH-plant height, EH-ear height, EPO-ear position, SL-stem lodging, RL-root lodging, TL-total lodging, NP-number of plants, σ^2G-genotypic variance component, σ^2E-error variance component, σ^2P-phenotypic variance component, ECV-error coefficient of variation and GCV-genetic coefficient of variation. The error DF for GY and SP are 254 and 253, respectively. *-significant at 5% probability level, ***-significant at 0.1% probability level.

Table 4.7 continued. Mean square values and their significance for hybrid traits studied at Dundee

Source	DF	MOI	AD	SD	ASI
Rep	3	3.52***	10.12***	16.11***	1.11
Rep.Block	36	0.84*	10.62***	8.22***	1.05*
NP	1	0.02	34.73***	36.49***	0.02
Entry	104	1.64***	8.73***	7.23***	0.90*
Residual	253	0.54	1.60	1.72	0.66
Total	398	0.88	4.43	3.95	0.76
Mean		13.99	74.34	74.89	0.55
σ^2G		0.28	1.78	1.38	0.06
σ^2E		0.54	1.60	1.72	0.66
σ^2P		0.81	3.38	3.10	0.72
ECV (%)		5.25	1.70	1.75	148.65
GCV (%)		3.76	1.80	1.57	44.47
Heritability		33.89	52.70	44.47	8.21

DF-degrees of freedom, MOI-moisture content, AD-anthesis date, SD-silking date, ASI-anthesis-silking interval, NP-number of plants, σ^2G-genotypic variance component, σ^2E-error variance component, σ^2P-phenotypic variance component, ECV-error coefficient of variation and GCV-genetic coefficient of variation. The error DF for MOI is 254. *-significant at 5% probability level, ***-significant at 0.1% probability level.

Table 4.8 Mean performance of top 10 and bottom 10 hybrids against checks at Dundee

Entry	Name	GY	SP	EPP	EL	PH	EH	EPO	SL	EL	TL	MOI	AD	SD	ASI
84	14PVAH-165	10.40	83.49	2.04	21.84	293.60	149.70	0.51	15.11	21.84	22.39	15.40	74.84	76.10	1.26
89	14PVAH-175	9.57	86.94	1.87	19.80	296.80	151.90	0.51	20.60	19.80	27.64	14.61	73.04	73.55	0.51
85	14PVAH-167	9.48	86.00	1.88	22.44	275.60	131.50	0.48	11.53	22.44	18.33	14.57	76.48	76.23	-0.25
52	14PVAH-102	9.33	83.32	1.94	19.90	271.70	128.00	0.47	12.78	19.90	21.94	15.00	75.56	75.81	0.24
81	14PVAH-159	9.24	81.41	1.81	22.06	277.10	126.80	0.46	11.45	22.06	18.06	14.74	78.43	78.67	0.24
61	14PVAH-120	9.23	82.37	1.87	21.40	287.00	132.90	0.46	8.17	21.40	17.05	14.53	74.76	75.48	0.72
88	14PVAH-173	9.21	87.47	1.81	19.41	269.60	121.30	0.45	10.04	19.41	16.56	13.69	74.75	75.23	0.48
15	14PVAH-29	9.12	82.29	1.84	20.57	285.60	130.70	0.46	11.72	20.57	21.74	14.40	75.78	75.28	-0.50
87	14PVAH-171	9.07	88.51	1.77	20.24	283.60	150.80	0.53	24.38	20.24	35.71	13.78	73.97	73.96	0.00
80	14PVAH-158	9.06	83.26	1.16	21.50	314.90	139.40	0.44	17.55	21.50	28.26	15.60	73.50	74.50	1.00
Mean of top 10 PVA hybrids		9.37	84.51	1.80	20.92	285.55	136.30	0.48	14.33	20.92	22.77	14.63	75.11	75.48	0.37
102	DKC80-40BRGEN	10.62	89.78	1.82	17.67	280.00	138.90	0.50	6.37	17.67	12.95	12.96	74.98	75.47	0.49
103	11C1579	9.02	84.87	1.16	21.42	274.20	123.40	0.45	10.88	21.42	17.88	13.24	74.54	75.05	0.51
104	11C1774	8.29	87.09	1.33	18.90	284.40	135.40	0.48	6.83	18.90	13.60	13.90	73.50	74.00	0.50
105	11C1483	8.27	87.73	1.34	19.50	281.90	117.40	0.42	6.83	19.50	13.60	13.10	74.00	74.50	0.50
101	PAN6Q308	6.32	81.07	1.03	13.56	242.90	101.10	0.42	66.24	13.56	72.35	15.21	79.62	80.46	0.84
Mean of all checks		8.50	86.11	1.34	18.21	272.68	123.24	0.45	19.43	18.21	26.08	13.68	75.33	75.90	0.57
% Genetic gain of PVA hybrids		10.20	-1.86	34.44	14.86	4.72	10.60	5.70	-26.23	14.86	-12.69	6.94	-0.29	-0.55	-34.70
Mean		7.68	83.36	1.47	19.93	267.92	125.97	0.47	14.27	19.93	22.30	13.99	74.34	74.89	0.55
% LSD		1.49	3.91	0.30	1.77	27.24	18.07	0.07	8.55	1.77	10.88	1.08	1.85	1.92	1.19
% CV		13.22	3.19	13.76	6.05	6.97	9.82	9.90	41.35	6.05	33.60	5.24	1.70	1.75	147.93

GY-grain yield, SP-shelling percentage, EPP-ears per plant, EL-ear length, PH-plant height, EH-ear height, EPO-ear position, SL-stem lodging, RL-rot lodging, TL-total lodging, MOI-moisture content, AD-anthesis date, SD-silking date, ASI-anthesis-silking interval, LSD-least significant difference and CV-coefficient of variation.

Table 4.9 Mean square values and their significance for hybrid traits studied at Cedara

Source	DF	GY	SP	EPP	EL	EA	GT	PH	EH	EPO
Rep	3	4.933*	25.26	0.01802	1.045	0.896	0.845	229.7	132.6	0.003254
Rep.Block	36	1.668	19.2	0.10837	6.762	2.329*	0.4727	511.4*	244.4	0.00368
NP	1	100.298***	0.87	0.8289***	0.46	5.768	0.0419	1798.4*	7528.7***	0.093352***
Entry	104	2.361***	28.77***	0.09922*	5.139	2.362**	1.0055*	509.6***	391.8***	0.005771***
Residual	255	1.42	14.95	0.07	4.92	1.54	0.71	301.00	184.30	0.003
Total	399	1.96	18.98	0.09	5.10	1.83	0.76	377.50	261.90	0.004
Mean		6.82	80.96	1.44	18.94	6.52	1.77	251.52	102.86	0.410
σ^2G		0.24	3.46	0.01	0.05	0.21	0.07	52.15	51.88	0.001
σ^2E		1.42	14.95	0.07	4.92	1.54	0.71	301.00	184.30	0.003
σ^2P		1.65	18.41	0.08	4.98	1.74	0.78	353.15	236.18	0.003
ECV (%)		17.43	4.78	18.96	11.71	19.02	47.62	6.90	13.20	12.767
GCV (%)		7.13	2.30	5.42	1.23	6.98	15.33	2.87	7.00	6.714
Heritability		14.32	18.77	7.57	1.10	11.87	9.39	14.77	21.96	21.664

DF-degrees of freedom, GY-grain yield, S-shelling percentage, EPP-ears per plant, EL-ear length, EA-ear aspect, PH-plant hight, EH-ear height, EPO-ear position, NP-number of plants, σ^2G-genotypic variance component, σ^2E-error variance component, σ^2P-phenotypic variance component, ECV-error coefficient of variation and GCV-genetic coefficient of variation. The error DF for EPP is 253. *-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 4.9 continued. Mean square values and their significance for hybrid traits studied at Cedara

Source	DF	SL	RL	TL	MOI	ASI	GLS	PLS	ET	ER
Rep	3	0.003	0.0003	0.0021	0.790	0.103	5.036	1.59	5.459	0.678
Rep.Block	36	0.004	0.0009	0.0043	0.820	0.190	3.870	1.96	3.418*	2.789
NP	1	0.024*	0.001	0.032375**	1.459	0.432	0.012	5.29	6.588	4.684
Entry	104	0.004	0.0012*	0.005	1.349***	0.191	4.299*	3.287***	3.820	4.148**
Residual	255	0.004	0.0008	0.0042	0.659	0.176	3.281	1.891	2.092	2.781
Total	399	0.004	0.0009	0.0044	0.857	0.182	3.605	2.267	2.698	3.127
Mean		0.045	0.0085	0.0535	14.120	-0.957	4.796	3.176	5.742	2.129
σ^2G		0.000	0.0001	0.0002	0.172	0.004	0.255	0.349	0.432	0.342
σ^2E		0.004	0.0008	0.0042	0.659	0.176	3.281	1.891	2.092	2.781
σ^2P		0.004	0.0009	0.0044	0.832	0.180	3.536	2.240	2.524	3.123
ECV (%)		135.853	333.9954	120.6205	5.750	-43.896	37.770	43.303	25.188	78.325
GCV (%)		12.770	110.7989	27.1074	2.941	-6.314	10.519	18.603	11.446	27.457
Heritability		0.876	9.9140	4.8077	20.741	2.027	7.198	15.580	17.116	10.944

DF-degrees of freedom, SL-stem lodging, RL-root lodging, TL-total lodging, MOI-moisture content, ASI-anthesis-silking interval, GLS-grey leaf spot, PLS-Phaesospharia leaf spot, ET-Turcicum leaf blight, ER-ear rot, NP-number of plants, σ^2G-genotypic variance component, σ^2E-error variance component, σ^2P-phenotypic variance component, ECV-error coefficient of variation and GCV-genetic coefficient of variation. *-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 4.10 Mean performance of top 10 hybrids against checks at Cedara

Entry	Name	GY	SP	EPP	EL	EA	GT	PH	EH	EPO
92	14PVAH-181	8.65	78.87	1.45	21.75	5.57		243.80	82.30	0.34
27	14PVAH-53	8.55	81.05	1.58	18.63	6.23	2.03	252.80	104.80	0.41
25	14PVAH-49	8.51	81.25	2.15	18.72	7.10	0.62	257.60	96.40	0.38
28	14PVAH-55	8.49	78.05	1.49	19.35	6.23	1.76	266.00	120.30	0.45
36	14PVAH-71	8.41	86.49	1.40	19.74	6.95	1.53	252.70	100.40	0.40
48	14PVAH-95	8.31	82.57	1.76	15.87	5.46	2.28	248.50	105.00	0.42
53	14PVAH-104	8.25	77.50	1.65	20.12	5.52	2.21	269.10	110.60	0.41
39	14PVAH-77	8.23	79.17	1.51	20.61	6.52	1.22	263.90	137.00	0.52
37	14PVAH-73	7.94	83.80	1.65	18.25	5.79	2.20	246.00	93.50	0.38
38	14PVAH-75	7.94	80.65	1.57	19.35	4.29	1.18	246.40	101.20	0.41
Mean of top 10 PVA hybrids		8.33	80.94	1.62	19.24	5.97	1.67	254.68	105.15	0.41
105	11C1483	6.75	82.17	1.30	19.25	5.49		266.80	95.80	0.36
101	PAN6Q308	6.35	70.86	1.56	19.75	5.45		261.60	103.80	0.40
104	11C1774	6.19	83.23	1.26	16.75	5.91		254.40	104.70	0.41
103	11C1579	5.39	73.23	1.32	18.75	3.95		229.60	94.80	0.41
102	DKC80-40BRGEN	4.87	71.38	1.50	17.25	3.95		236.60	93.80	0.40
Mean of all checks		5.91	76.17	1.39	18.35	4.95		249.80	98.58	0.40
% Genetic gain of PVA hybrids		40.98	6.26	16.84	4.84	20.50		1.95	6.66	4.31
Mean		6.82	80.96	1.44	18.94	4.97	1.77	251.52	102.86	0.41
5% LSD		1.74	5.65	0.40	3.24	2.17	1.11	25.36	19.84	0.08
% CV		17.37	4.77	18.93	11.71	29.68	47.74	6.89	13.17	12.77

GY-grain yield, SP-shelling percentage, EPP-ears per plant, EL-ear length, EA-ear aspect, PH-plant hight, EH-ear height, EPO-ear position, LSD-least significant difference and CV-coefficient of variation.

Table 4.10 continued. Mean performance of top 10 hybrids against checks at Cedara

Entry	Name	SL	RL	TL	MOI	ASI	GLS	PLS	ET	ER
92	14PVAH-181	0.007	0.0340	0.041	15.16	-1.00	3.01	5.48	6.52	2.56
27	14PVAH-53	0.043	0.0001	0.043	14.75	-1.00	3.75	4.24	6.73	1.74
25	14PVAH-49	0.086	0.0079	0.094	13.29	-1.56	3.92	2.47	6.16	1.97
28	14PVAH-55	0.029	0.0000	0.029	14.57	-0.50	2.50	4.25	8.00	0.74
36	14PVAH-71	0.041	0.0147	0.056	14.87	-1.00	2.24	4.50	7.00	2.71
48	14PVAH-95	-0.003	0.0146	0.012	14.00	-1.00	2.49	3.25	6.48	0.97
53	14PVAH-104	0.100	0.0003	0.100	15.25	-1.01	2.74	5.74	7.26	4.26
39	14PVAH-77	0.062	0.0159	0.077	14.94	-1.00	3.75	5.72	6.02	1.53
37	14PVAH-73	0.082	0.0005	0.083	15.04	-1.01	3.00	3.72	6.98	4.28
38	14PVAH-75	0.023	0.0005	0.023	15.25	-1.01	3.01	4.23	7.51	1.79
Mean of top 10 PVA hybrids		0.047	0.0088	0.056	14.71	-1.01	3.04	4.36	6.87	2.25
105	11C1483	-0.001	-0.0001	-0.001	14.00	-1.00	2.50	3.00	7.50	1.99
101	PAN6Q308	0.142	-0.0005	0.142	13.24	-1.00	2.99	3.52	6.49	5.46
104	11C1774	0.047	-0.0008	0.046	13.59	-0.98	2.48	3.03	7.98	1.93
103	11C1579	0.024	-0.0005	0.024	13.09	-0.49	1.99	3.52	6.49	1.96
102	DKC80-40BRGEN	0.113	-0.0005	0.112	12.89	-1.00	1.99	3.02	4.99	3.96
Mean of all checks		0.065	-0.0005	0.065	13.36	-0.89	2.39	3.22	6.69	3.06
% Genetic gain of PVA hybrids		-27.781	-1998.5401	-13.563	10.10	13.10	27.32	35.62	2.65	-26.33
Mean		0.045	0.0085	0.053	14.12	-0.96	2.66	4.05	6.61	2.13
LSD		0.089	0.0414	0.094	1.19	0.62	1.51	2.52	2.11	2.44
CV		136.650	341.6000	121.640	5.74	-43.77	38.84	42.32	21.88	79.22

SL-stem lodging, RL-root lodging, TL-total lodging, MOI-moisture content, ASI-anthesis-silking interval, GLS-grey leaf spot, PLS-Phaesospharia leaf spot, ET-Turcicum leaf blight, ER-ear rot, LSD-least significant difference and CV-coefficient of variation.

Table 4.11 Mean performance of top 10 hybrids against checks across three sites

Entry	Name	GY	EPP	EL	PH	EH	EPO	MOI	ASI
54	14PVAH-106	7.50	1.51	20.39	267.00	112.20	0.41	15.32	0.26
61	14PVAH-120	7.41	1.59	19.98	271.90	118.60	0.44	15.54	0.41
5	14PVAH-9	7.38	1.49	20.71	267.80	119.20	0.44	14.58	-0.31
60	14PVAH-118	7.36	1.30	20.03	281.60	122.50	0.43	15.82	0.65
87	14PVAH-171	7.23	1.47	20.32	265.80	125.90	0.47	14.74	-0.33
20	14PVAH-39	7.23	1.34	21.34	273.60	115.60	0.42	15.34	0.01
39	14PVAH-77	7.22	1.25	19.20	273.80	136.30	0.50	14.57	0.08
81	14PVAH-159	7.21	1.49	21.21	265.60	126.10	0.47	15.10	0.66
84	14PVAH-165	7.14	1.46	21.15	269.00	135.50	0.50	15.32	0.61
40	14PVAH-79	7.14	1.24	20.06	268.80	110.90	0.41	14.37	0.00
Mean of top 10 PVA hybrids		7.28	1.41	20.44	270.49	122.28	0.45	15.07	0.20
102	DKC80-40BRGEN	6.67	1.52	17.28	260.30	119.00	0.46	13.47	0.18
105	11C1483	6.52	1.22	20.16	269.50	105.80	0.39	14.18	-0.15
104	11C1774	6.34	1.21	18.53	260.20	119.30	0.46	14.40	0.19
103	11C1579	6.19	1.16	20.63	258.40	119.80	0.46	14.19	0.02
101	PAN6Q308	5.09	1.18	17.76	257.00	106.20	0.41	14.66	-0.12
Mean of checks		6.16	1.26	18.87	261.08	114.02	0.44	14.18	0.02
% Genetic gain of PVA hybrids		18.20	12.58	8.30	3.60	7.24	3.12	6.28	848.23
Mean		6.50	1.33	19.98	260.42	116.68	0.45	14.83	0.15
5% LSD		0.91	0.19	1.43	13.86	10.55	0.04	0.66	0.83
% CV		16.68	16.58	8.55	6.37	10.78	10.63	5.30	653.89

GY-grain yield, EPP-ears per plant, EL-ear length, PH-plant height, EH-ear height, EPO-ear position, MOI-moisture content, ASI-anthesis-silking interval, LSD-least significant difference and CV-coefficient of variation.

Table 4.12 continued. Mean performance of top 10 hybrids against checks across two sites

Entry		Name	SP	SL	RL	TL	AD	SD
	54	14PVAH-106	83.19	9.15	4.27	13.38	66.78	67.66
	61	14PVAH-120	82.52	3.96	4.33	8.32	67.05	68.17
	5	14PVAH-9	82.75	4.80	3.83	8.49	67.92	68.08
	60	14PVAH-118	81.45	5.17	3.29	8.51	66.89	68.36
	87	14PVAH-171	83.65	12.12	5.58	17.75	66.53	66.54
	20	14PVAH-39	82.25	6.37	6.40	12.76	67.63	68.26
	39	14PVAH-77	81.97	5.04	3.29	8.36	64.09	64.71
	81	14PVAH-159	80.83	6.08	3.44	9.59	69.34	70.80
	84	14PVAH-165	82.64	7.53	3.73	11.14	67.77	69.17
	40	14PVAH-79	83.58	5.14	3.33	8.45	66.75	67.27
Mean of top 10 PVA hybrids			82.48	6.54	4.15	10.68	67.08	67.90
	102	DKC80-40BRGEN	80.57	3.60	3.52	7.11	66.57	67.33
	105	11C1483	84.95	3.44	3.42	6.85	66.97	67.23
	104	11C1774	85.16	3.90	3.75	7.57	66.30	67.06
	103	11C1579	79.09	5.58	3.65	9.15	68.77	69.03
	101	PAN6Q308	74.30	36.50	29.32	41.58	71.05	71.30
Mean of checks			80.81	10.60	8.73	14.45	67.93	68.39
% Genetic gain of PVA hybrids			2.07	-38.37	-52.50	-26.13	-1.26	-0.71
Mean			82.14	7.18	4.27	11.21	66.55	67.25
5% LSD			3.42	4.36	3.07	5.63	1.39	1.39
% CV			4.04	59.75	72.14	49.32	2.03	2.01

SP-shelling percentage, SL-stem lodging, RL-root lodging, TL-total lodging, AD-anthesis date, SD-silking date, LSD-least significant difference and CV-coefficient of variation.

Table 4.13. Phenotypic correlation coefficients among traits studied across locations

EPP	0.31**														
EL	0.28**	-0.46***													
MOI	0.31**	0.01	0.26*												
AD	0.28**	0.13	0.41***	0.24*											
SD	0.28**	0.07	0.49***	0.34**	0.93***										
ASI	-0.03	-0.18	0.11	0.24*	-0.36**	0.00									
EH	0.35***	-0.05	0.24*	0.25*	0.35***	0.37***	0.01								
PH	0.55***	0.00	0.33**	0.44***	0.46***	0.52***	0.08	0.69***							
SL	-0.19	0.18	-0.29**	0.07	-0.15	-0.21	-0.11	-0.05	-0.18						
RL	-0.01	0.07	-0.12	0.13	0.00	-0.02	-0.04	0.15	0.08	0.54***					
TL	-0.15	0.16	-0.26*	0.10	-0.11	-0.16	-0.10	0.01	-0.11	0.96***	0.76***				
EA	0.23*	0.17	-0.15	-0.13	-0.06	-0.17	-0.26*	-0.17	-0.17	-0.19	-0.25*	-0.23*			
TLB	-0.08	-0.10	0.06	0.10	0.01	0.13	0.34**	0.34**	0.18	0.07	0.14	0.09	0.31**		
GLS	0.20	0.01	0.05	-0.10	0.11	0.05	-0.19	0.09	0.18	-0.22*	-0.16	-0.22*	0.23*	-0.02	
PLS	0.14	0.13	0.00	0.23*	0.11	0.17	0.16	0.19	0.19	-0.17	-0.11	-0.17	0.06	0.17	0.09
	GY	EPP	EL	MOI	AD	SD	ASI	EH	PH	SL	RL	TL	EA	TLB	GLS

GY-grain yield, EPP-ears per plant, EL-ear length, MOI-moisture content, AD-anthesis date, SD-silking date, ASI-anthesis-silking interval, EH-ear height, PH-plant height, SL-stem lodging, RL-root lodging, TL-total lodging, EA-ear aspect, TLB-*Turcicum* leaf blight, GLS-gray leaf spot.

A total of eight traits (EPP, EL, MOI, AD, SD, EH, PH and EA) were found to be significantly (P<0.01) correlated (r = 0.23-0.55) with grain yield across the four locations. Several other correlations among traits were found that include EA with RL (p<0.05, r = -0.25), EA with TL (p<0.05, r = -0.23) and AD with SD (p<0.001, r = 0.93) (Table 4.13). Some positive correlations were found between ear height and ear position, root lodging and total lodging as well as stem lodging and total lodging (Table 4.13).

4.5.6 Genotype comparison based on grain yield and stability

Hybrids 14PVAH-106 (54) and 14PVAH-120 (61) are found in the inner most circle, closer to the average environment (Fig 1). However, most check hybrids are found glutted together with some PVA hybrids but further away from the inner most circle. Check hybrids DKC80-40BRGEN (102), 11C1579 (103) and 101(PAN6Q308) are found closer or below the line that runs perpendicular to the average environment axis (Fig 1).

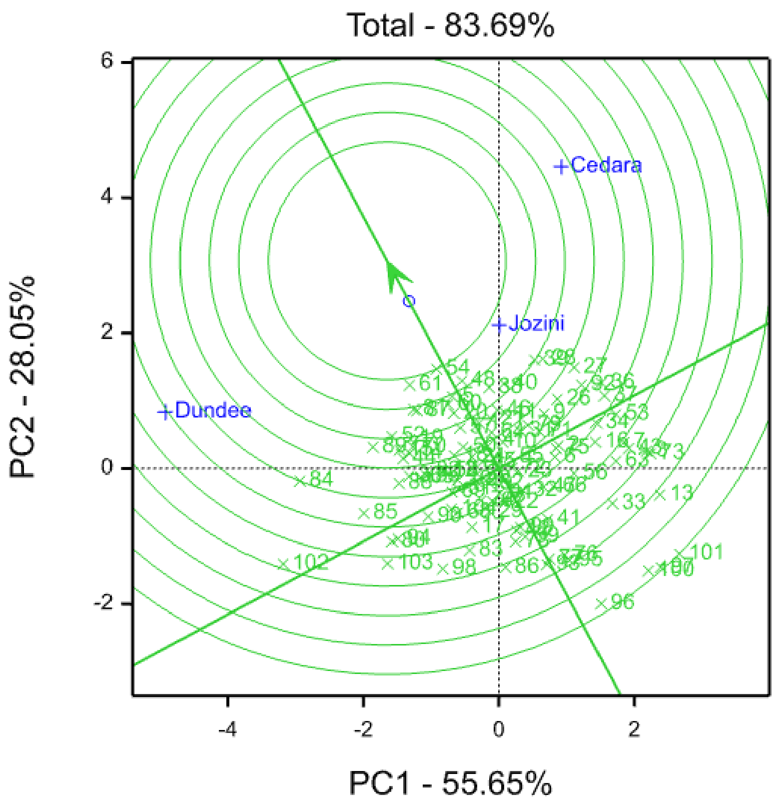

Figure 4.1 A comparison biplot showing hybrids mean yield and stability across sites, and hybrids are shown by their entry codes in order to reduce congestion.

4.6 Discussion

The highly significant differences found among hybrids based on single site and across site analyses show that there were huge variation among the performance of the hybrids for grain yield and allied traits. Indeed, heritability values were moderate to relatively high, thus suggesting the possibility of selecting desirable hybrids with the potential to out-perform the standard checks used (Maphumulo *et al*., 2015). In addition to low disease scores (ET), the PVA hybrids that outperformed the check had higher shelling percentages, longer ears, near zero ASI values and relatively high moisture content compared to the check hybrids (Table 4.12). High shelling percentage would result into more grain and high grain yield. Genotypes with lower shelling percentages have been associated with lesser grain yield in maize. Longer ears would imply more kernels per row, a parameter that is associated with high grain yield. Grain yield is a function of number of kernels and kernel weight (Borrás, 2007), and the number of kernels is associated with ear length (Hallauer and Miranda, 1988). Negative and near zero ASI values are associated with improved synchronization under both stress (Banziger *et al*., 2004; Derera *et al*., 2007) and non-stress conditions (Basseti and Westgate, 1994). Improved synchronization has an effect of increasing kernel set thus improving grain number per ear. In the recent past, the breeding of hybrids with shorter or negative ASI has been found useful in improving grain yield across diverse environments (Banziger *et al*., 2006). The association of high yield in PVA hybrids with high moisture content could reflect the effects of maturity on grain yield. Late hybrids are associated with high moisture content than early ones. This implies that the hybrids with high moisture content could be late, and late maize has been known to yield higher than early maturing genotypes (Gasura *et al*., 2013). In this situation a number of parameters must be considered when breeding successful hybrids that can out-perform the checks on the market. Lee and Tollenaar (1999) reported that most traits have been pushed to the optimum and breeders must wisely select for some traits that seem to increase genetic gains. Duvick *et al.* (2010) highlighted that the genetic improvements in tropical maize could be enhanced by breeding for stress tolerance that include high density, diseases and drought stress. Masuka *et al.* (2017a, b) and Setimela *et al.* (2017b) estimated the genetic gains obtained from maize germplasm bred at CIMMYT. In all their studies, genetic gains were higher with drought tolerant and high nitrogen use efficiency compared to optimum conditions. In this regard, the success of PVA hybrids that outperformed the local checks could be attributed to high shelling percentages, longer ears, and traits that increases that adaptability across environments such as shorter ASI and resistance to the major diseases, as well as resistance to stem and root lodging to facilitate high plant stands. However, there are some traits which are crucial in breeding maize with high yield. These traits include high EPP, as well as selecting maize hybrids with desirable PH, EH and EPO. The later parameters are considered essential depending on whether the combine harvester or hand harvesting would be done. Very tall plants and very short plants increases harvesting labour and thus such hybrids are less liked by farmers. In terms of the PVA hybrids developed, they seemed to be performing well for these traits since they performed as the standard hybrids used as checks.

The large variance component due to genotype by environment interaction presents a huge challenge in breeding PVA hybrids adapted to various areas. When the genotype by environment interaction is present, it must not be ignored (Bernado, 2002). However, GE can be exploited by selecting genotypes for specific areas, stratification of the environments into mega-environments or identifying hybrids with stable and high mean yield (Yan and Tinker, 2006). Given the fact that the number of locations used in this study were few, the feasible approach would be to identify high yielding and stable genotypes. In this regard, the most stable hybrids were found in the inner most circle of the comparison biplot, closer to the average environment coordinate. These hybrids include 14PVAH-106 (54) and 14PVAH-120 (61), and were more stable and high yielding than the standard commercial hybrids used in the study. Stable hybrids have an advantage of maintaining above average yield across low environments while producing high yields across high yielding environments (Finlay and Wilkinson, 1963).

The production of PVA maize hybrids has been associated with several nutritional advantages especially among children and pregnant women. However, farmers would not be willing to accept a hybrid that yields less than the standard checks (Kamutando *et al*., 2013; Setimela *et al*., 2017a). High grain yield could therefore be used as the buy-in by the farmers to encourage them to adopt PVA maize. PVA maize is more likely to be adopted by the livestock farmers faster than when it used for human consumption

The high and significant correlations between grain yield and other secondary traits can be explained on the basis of grain yield formation physiology (Gasura et al., 2013). It has been widely reported that late maturing maize yield more than early maturing maize (Gasura et al., 2014). In this regard, all traits that are associated with maturity such as plant height, ear height, silking date and anthesis date will be highly correlated with grain yield. Furthermore, ear aspect, ears per plant and ear length are all associated with yield. If a maize genotype has more than one cob, developed under non-stress conditions, it also gives more yield than the one with single cobs. Furthermore, if the ear is longer, it tends to have more grains per cob thus higher grain yield. The negative correlations between ear aspect and both root and stem lodging can be expected. When the ear aspect is good, the cobs are well developed to the extent that they can cause root and stem lodging especially under high population density. However, some correlations such as of anthesis date and silking date could indicate the plant phenology such that plants with early silking tend to have early anthesis and vice versa. Furthermore, some correlations such as ear position and ear height as well as root/ stem lodging with total lodging could indicate ways in which these traits are related in terms of measurements or calculations.

4.7 Conclusions and recommendations

4.7.1 Conclusions

The following conclusions could be drawn:

- The genotype by environment interaction was high among the PVA hybrids studied.
- Hybrids 14PVAH-106 (54) and 14PVAH-120 (61), were high yielding and stable across environments.
- The high yield and stability of these hybrids was associated with longer ear length, high shelling percentage, near zero ASI values and resistance to diseases and lodging.
- Some secondary traits such as ears per plant and ear aspect are good predictors of grain yield that can be used for indirect selection in breeding orange maize.

4.7.2 Recommendations

The following recommendations are made:

- Hybrids 14PVAH-106 (54) and 14PVAH-120 (61), that were high yielding and stable across environments could be recommended for further testing and release.
- Traits such as longer ear length, high shelling percentage, near zero ASI values and resistance to diseases and lodging must be considered as key in selecting PVA hybrids that can outperform the commercial standards.

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Chapter 5 : GENETIC ANALYSIS

Combining ability and gene action for grain yield and allied traits among the pro-vitamin A (PVA) and non-PVA maize germplasm

Abstract

Malnutrition, especially vitamin A deficiency (VAD) is rampant in Sub-Saharan Africa. Bio-fortification of the major staple crops such as maize is the cheapest option of providing adequate nutrition to a large number of resource limited people. However, breeding efforts targeting improvement of pro-vitamin A (PVA) maize has been lagging behind in sub-Saharan Africa due to absence of genetic information on this trait. The concept of combining ability has been widely used to study gene action and to identify desirable inbred lines and hybrids in maize breeding. However, this information on combining ability in PVA maize is scarce, especially in the tropical maize germplasm. A set of 10 PVA maize inbred lines were crossed to another set of 10 inbred lines that were composed of PVA, QPM and normal maize inbred lines in a line x tester mating scheme. The resultant 100 single cross hybrids were evaluated using a 10 x 10 α-lattice design with two replications across four sites Cedara, Dundee, Jozini and Ukulinga in South Africa. Data on grain yield and related traits were subjected to line x tester analysis of variance. The general combining ability (GCA) and specific combining ability (SCA) effects were calculated for grain yield and allied traits. The variance components for the lines, testers, line x tester hybrid and also their interactions with the environment were estimated. The Baker's ratio, broad sense and narrow sense heritability were estimated from the variance components for each trait. Analysis of variance showed that lines, tester hybrids and line x tester as well as their interactions with the sites were significant ($P<0.05$) for most traits including grain yield. There were huge effects of the sites that would modify the genotypic effects across environments. Additive gene action was predominant in the control of most traits studied including grain yield as evidenced by the Barker's ratios that were above 50% for most traits. Narrow sense heritability was low (<50%) for grain yield and other allied traits except silking date and anthesis date that had medium (50-80%) values. This suggested the need for evaluation of the testcross performance in many locations in order to identify desirable inbred lines and hybrids. Desirable inbred lines were identified as line 5 and 6 and tester 1 and 5, while the desirable crosses were 6 x 1 and 5 x 1. Tester 5 is a non-PVA line, thus suggesting the importance of widening the genetic base in hybrid development.

5.1 Introduction

Maize is the major staple crop in many sub-Saharan African countries where malnutrition especially vitamin A deficiency (VAD) is high (Nyakurwa *et al*., 2017). Despite the VAD challenges being faced by people in this region, there are several options that can be deployed to reduce its effects (Kapinga *et al*., 2003). One such approach would be bio-fortification of maize that is breeding of maize varieties with increased levels of pro-vitamin A (PVA), a precursor of vitamin A, in the carotenoid biosynthesis pathway (Giuliano, 2008). Bio-fortification of the major staple crop is a relatively new idea that was successfully implemented in some crops such as sweetpotato (Kapinga *et al*., 2003). However, specific crops have different breeding approaches that require understanding of different genetic information (Griffing, 1956).

In maize, breeding efforts targeting bio-fortification of this crop, requires understanding of some genetic information on grain yield and other essential traits (Maphumulo *et al*., 2015). The main information needed is on the combining ability and gene action governing the major traits in PVA maize germplasm (Egesel *et al*., 2003). Maize hybrid formulation requires identification of desirable inbred lines based on their *per se* performance and also based on their performance in various hybrid combinations (Pswarayi and Vivek, 2008). Information on combining ability was widely used in maize breeding in the selection of desirable inbred lines and hybrids (Pswarayi and Vivek, 2008). Inbred lines for use in future breeding activities must possess high and desirable general combining ability effects for traits of economic importance. For example, a desirable inbred line could possess high positive general combining ability (GCA) effects for grain yield, shelling percentage, ears per plant but should have high negative or near to zero GCA effects for lodging, disease scores and other traits whose mean should be decreased in a given hybrid (Gasura *et al*., 2013). In maize breeding, development of new lines would involve crossing inbred lines with desirable GCA effects as predicted from their test cross performance.

A desirable hybrid on the other hand should possess desirable (either positive or negative) specific combining ability effects depending on the trait (Hallauer and Miranda, 1988). However, the specific combining ability (SCA) effects for grain yield are highly considered in a hybrid breeding program. Furthermore, a hybrid must show not only high desirable SCA effects but also high *per se* performance for a given trait (Pswarayi and Vivek, 2008). The occurrence of high SCA effects values for grain yield is highly correlated to heterosis. Heterosis, a phenomena where the hybrid performs better than the parents is an indicator of genetic variability (Amiruzzaman et al., 2013). When divergent inbred lines are crossed, heterosis is expected to be high (Hallauer et al., 2010). Thus in some cases where the information on heterosis is absent, SCA effects values can be used to group inbred lines into their heterotic groups (Hallauer *et al*., 2010; Pswarayi and Vivek, 2008). In this study, a set of 10 testers, coming from divergent inbred lines that is PVA lines, normal maize and quality protein maize inbred lines were used in an attempt to maximize heterosis. The objective of this study was to determine the combining ability and gene action among the PVA and non-PVA maize inbred lines.

5.2 Materials and methods

5.2.1 Plant materials

A set of 20 lines (Table 5.1) were planted at Makhathini (77m altitude; Latitude 27.39^{0}S; Longitude 32.17^{0}E), and Ukulinga Research Farm (806m Altitude; Latitude 29.66^{0}S Longitude 30.40^{0}E) during the 2012/2013 summer season. Staggered planting of the lines was employed to synchronize flowering. This entailed three planting dates at a weekly interval. The 20 lines were crossed using a 10 x 10 North Carolina design II mating scheme to generate 100 single cross hybrids.

Table 5.1 Description of features of 20 maize inbred lines used in developing hybrids

Entry	Pedigree	Parent type	Grain type	Characteristics
1	12UK15-13	Line	PVA	Long ear, slight lodging, prolific
2	12UK15-10	Line	PVA	Long ear, good standing ability
3	12UK15-15	Line	PVA	Very prolific, good standing ability, high yield
4	12UK15-18	Line	PVA	Long ear, good standing ability
5	12UK15-21	Line	PVA	Long ear, susceptible to lodging
6	12UK15-32	Line	PVA	High seed yield, good standing ability
7	12UK15-33	Line	PVA	Long ear, susceptible to lodging
8	12UK15-36	Line	PVA	High seed yield, good standing ability
9	12UK15-58	Line	PVA	Very long ear, good standing ability, good yield
10	12UK15-60	Line	PVA	Long ear, good standing ability
11	12CR3-7	Tester	PVA	CIMMYT line, long ear, high yield and high vitamin A
12	12CR3-8	Tester	PVA	CIMMYT line, long ear
13	12CR3-9	Tester	PVA	CIMMYT line, short ear
14	12CR3-22	Tester	QPM	QPM, medium ear, yellow
15	12CR3-25	Tester	QPM	QPM, medium ear, yellow
16	12CR3-26	Tester	QPM	QPM, long ear, yellow
17	12UK20-7	Tester	NM	High yield, prolific, yellow normal maize (non PVA and QPM)
18	12UK40-14	Tester	NM	High yield, prolific, yellow normal maize (non PVA and QPM)
19	12UK20-12	Tester	NM	High yield, prolific, yellow normal maize (non PVA and QPM)
20	12UK16-14	Tester	NM	Temperate, high yield potential, yellow

CIMMYT-International Maize and Wheat Improvement Center, NM-Normal Maize, PVA-pro-vitamin A maize inbred lines, QPM-quality protein maize inbred line.

5.2.2 Description of trial sites

Hybrids were evaluated at four sites Cedara, Dundee, Jozini, and Ukulinga). The geographical descriptions of the sites are given in Table 5.2. The soil in the testing field of Ukulinga Research Farm is sandy clay-loam, fertile and friable with good water drainage (Cambisol). It is composed of 35% sand, 44% silt, 21% clay, 7.4 pH, 1.2% organic matter, 10.32 ppm available phosphorous (P), and cation exchange capacity (CEC) of 22.34 (meq/100 g). However, it is susceptible to cracking and crusting under flooding. Cedara Research Station is characterised by sandy clay soils which are reasonably fertile and well drained. Chances of flooding were very low due to a good slope and ground cover. The fields at Ukulinga and Dundee were disc ploughed before planting although minimum tillage was done at Cedara. The Cedara field had high organic matter from the stover of preceding maize crop. The ground cover also provided mulch and helped in moisture conservation.

Table 5.2 Geographical coordinates and environmental conditions for the study sites

Sites	**Latitude**	**Longitude**	**Altitude (metres above sea level)**	**Total annual rainfall (mm)**	**Temperature range (ºC)**
Cedara	29°.54’S	30°.26’E	1068	696.96	9.85 – 24.41
Dundee	28°.13’S	30°.31’E	1219	782.80	9.70 – 24.10
Jozini	27°.39’S	32°.10’E	77	-	-
Ukulinga	29°.66’S	30°.40'E	809	676.17	13.65 – 24.83

5.2.3 Experimental design and trial management

The 100 hybrids (Table 5.2) were evaluated across four sites in KwaZulu-Natal province of South Africa, during the 2013/14 summer cropping season. Two boarder rows were planted at the ends, around the experimental sites. All experiments were laid out as incomplete block designs consisting of 10 x 10 α-lattice design with 4 replications at all the sites. Each plot consisted of two rows of 5m length. Plants were spaced at 30 cm within rows and 90 cm between rows, giving a total of 32 plants per plot. A total of 250 kg/ha NPK (56N: 83P: 111K) compound fertilizer was applied as basal dressing during planting, immediately after planting curator was applied around the experimental site to repel rodents. The field was irrigated to establish the crop. Six weeks after planting, 250 kg/ha of lime ammonium nitrate (LAN 28% N) was applied as a top dressing. Weed control was achieved through both chemical such as Basagran (to kill nutsedge), Gramoxone (all fresh weeds) and Troopers (broadleaf weeds including morning glory) and hand weeding, and all sites were rainfed until hand harvesting after physiological maturity.

5.3 Data collection

Data was collected following the standard protocols which are used at International Maize and Wheat Improvement Center (CIMMYT). Grain yield was measured as grain mass per plot adjusted to 12.5% grain moisture content at harvest. Ear prolificacy (EPP) was measured as the total number of ears per plot divided by the total number of plants per plot. Ear length was measured in cm from the tip of the cob to the base of the cob. Shelling percentage (SP) was measured as the grain weight per ear divided by the ear weight before shelling. Grain moisture content (MOI) was measured as percentage water content of grain measured at harvest. Days anthesis (AD), number of days after planting when 50% of the plants shed pollen. Days to silking (SD), number of days after planting when 50% of the plants showed silks. Anthesis-silking-interval (ASI), SD-AD. Plant height (PH) (cm) was measured as the distance from the base of plant to the insertion point of the top tassel. It was measured when all the plants had flowered, since plants reach their maximum height at flowering. Ear height (EH) (cm) was measured as height from ground level up to the base of the upper most ear. Ear position was measured as the ratio of ear height to plant height. Root lodging (RL) was measured as a percentage of plants that showed lodging by being inclined by up to 45°. Stem lodging (SL) was measured as a percentage of plants that were broken below the ear. Total lodging (TL) was measured as the sum of root lodging (RL) and stem lodging (SL). Diseases that include grey leaf spot, turcicum leaf blight, ear rots and phaeosphaeria leaf spot were measured based on a 1-5 scale where 1 is a clean plant where 5 is a severely diseased plant. Ear aspect was measured on a scale of 1 -5 where 1 is excellent and five is bad while grain texture was measured on a scale of 1-5 where 1 is flint while 5 is dent.

5.4 Data analysis

Line x tester analysis of variance was performed using the GenStat software. Grain yield for each plot was adjusted to tonnes ha^{-1} at 12.5% moisture content. The mathematical model of the line x tester for individual and across sites was expressed as: $Y_{ijkl} = \mu + l_j + t_k + lt_{jk} + e_{ijkl}$ and $Y_{ijkl} = \mu + s_i + l_j + t_k + lt_{jk} + sl_{ij} + st_{ik} + slt_{ijk} + e_{ijkl}$, respectively, where, Y_{ijkl} is the l^{th} observation at the i^{th} site on the jk^{th} progeny,

μ is the general mean, s_i = site main effects, l_j is the effects of the j^{th} line, (GCA effects for line), t_k is the effects k^{th} tester, (GCA effects for tester), $(lt)_{jk}$ is the interaction effect of the cross between the j^{th} line and k^{th} tester (SCA effects), sl_{ij}, st_{ik} and slt_{ijk} interaction of sites with the lines, testers and line x tester effects, and e_{ijkl} is the error term associated with each observation.

To estimate general combining ability (GCA) effects, their standard error and their mean square were estimated using the line x tester analysis using the following equations adapted from Hallauer *et al*. (2010): $GCA = \chi i - \mu$, where: GCA = general combining ability, χ_i = predicted mean of line or tester, μ = grand mean

Standard error for GCA effects were estimated following a methodology presented in Dabholkar (1999)

$$SE = \sqrt{\frac{\mathrm{MSEl}}{\mathrm{E} * \mathrm{T}}}$$

Where:

SE = standard error

MSE_l = mean square for lines

T = number of testers

E = number of environments

$$GCA_l = \frac{y_l}{rl} - \mu$$

$$GCA_t = \frac{y_t}{rt} - \mu$$

Where;

GCA_l and GCA_t = the general combining ability effect of the l^{th} line and t^{th} tester, respectively.

yl and y_t = the grand total of the i^{th} line mated with all testers and the t^{th} tester mated with all lines, respectively

μ= the grand mean of all crosses in all sites

r = the number of replications

l^{th}= the number of lines

t^{th}= the number of testers

The variance components from the line x tester analysis of variance were used to estimate heritability estimates. Heritability (broad, H^2 and narrow, h^2) were calculated using the following formulas:

$$H^2 = \frac{\sigma^2_{GCAl} + \sigma^2_{GCAt} + \sigma^2_{SCA}}{\sigma^2_{Sl} + \sigma^2_{St} + \sigma^2_{Stl} + \sigma^2_{tl} + \sigma^2_{t} + \sigma^2_{l} + \sigma^2_{e}}$$

$$h^2 = \frac{\sigma^2_{GCAl} + \sigma^2_{GCAt}}{\sigma^2_{Sl} + \sigma^2_{St} + \sigma^2_{Stl} + \sigma^2_{tl} + \sigma^2_{t} + \sigma^2_{l} + \sigma^2_{e}}$$

Where:

H^2= Broad sense heritability

h^2= Narrow sense heritability

σ^2_{GCAl} = Variance due to GCA of lines

σ^2_{GCAt} = Variance due to GCA of testers

σ^2_{SCA} = Variance due to SCA of lines x testers

The genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) were calculated for all quantitative traits, according to Singh and Chaudhary (2004), using the following equations:

$$GCV (\%)=\sqrt{\sigma^2 g}/x \times 100$$

$$PCV (\%)=\sqrt{\sigma^2 p}/x \times 100$$

Where,

$\sigma^2 g$ = genotypic variance,

$\sigma^2 p$ = phenotypic variance and

X = grand mean of the character.

5.5 Results

5.5.1 Individual sites

At individual sites the lines, testers and line x tester components were significant (P<0.05) for most traits studied (Table 5.3-Table 5.6 Other desirable inbred lines based on single site performance were 1, 5, 7, 9 and 10 (Table 5.7-Table 5.10). The testers 1, 2, 5, 6, 7 and 8 had positive GCA effects for grain yield for at least one site studied (Table 5.11-Table 5.14). Some of the hybrids such as line 5 x tester 6, had positive SCA effects for grain yield at single sites (Table 5.15-5.18) although, the top 10 winning hybrids across sites (Table 5.28) were not necessarily the top winners at individual sites except line 5 x tester 6 which was one of the best hybrids at Cedara. At individual sites, the GCA variance components were frequently larger than the SCA variance component (Table 5.19-Table 5.22). Furthermore, narrow sense heritability was low (<50%) to medium (50-80%) for almost all traits studied at single locations (Table 5.19-Table 5.22).

5.5.2 Across sites

There were highly significant differences (P<0.001) among genotypes, lines, testers for grain yield, ASI, SL, SP, AD, SD, TL, EH, EPO, MOI and PH except the lines that were significantly different at P<0.05 for SL (Table 5.23, Table 5.24 and Table 5.25) . However, genotypes, lines and testers did not show significant differences for EPP, EL and RL. Line x tester hybrids were as significantly different at P<0.01 for EPP, EL, SP and PH while there were significantly different at P<0.001 for MOI, AD, SD, EH and EPO (Table 5.23, Table 5.24 and Table 5.25). However, no significant differences were found under line x tester for GY, ASI, RL, SL, TL. The site x genotype, site x line, site x tester were significantly different for GY, EL, MOI and ASI, SL, SP, SD, AD, TL, EH and PH except site x line which was significant at P<0.05 for

SL and EPO which was not significant for site x tester (Table 5.23, Table 5.24 and Table 5.25). However, EPP and RL were not significantly different for all these sources of variation. Site x line x tester was significantly different at P<0.001 for EPP, EH and EPO while significantly different at P<0.01 for MOI, ASI, SP and PH; and significantly different at P<0.05 for GY, TL and SD. However, no significant differences were found on EL, RL, SL, and AD (Table 5.23, Table 5.24 and Table 5.25).

Lines 1, 3, 4, 5, 6, 7 and 9 have positive GCA effects for grain yield while lines 10, 2 and 8 had negative GCA effects for grain yield (Table 5.26). Interestingly some lines with positive GCA effects for yield such as 6 and 7 had also positive GCA effects for shelling percentage but very low GCA effects for total lodging and ASI among other traits (Table 5.26). Tester 10, 4, 5, 8 and 9 had positive GCA effects for grain yield (Table 5.27). Furthermore, these testers had positive GCA effects for other desirable traits such as SP and negative or small GCA values for traits such as ASI and TL (Table 5.27). Crosses from lines and testers 1 x 5, 5 x 6, 6 x7, 5 x8, 7 x1, 10 x 2, and 9 x 7 had positive SCA values for grain yield (Table 5.28).

The Baker's ratio was above 50% for all traits except for MOI, EPO, and RL. Narrow sense heritability was low (below 50%) for all traits except AD and SD which had moderate narrow sense heritability (between 50 and 80%) (Table 5.29). However, in all cases the error variance was larger than the genotypic variance for all traits studied across the four locations (Table 5.29).

Table 5.3 Mean square values for grain yield and other traits at Dundee

Site Dundee	DF	GY	EPP	MOI	AD	SD	ASI	TL	EH	EPO	PH	RL	SL	SP	EL
REP	3	3.424****	0.044***	2.379***	1.668	4.160***	0.843***	158.227***	7.391	0.003***	341.583**	7.742	116.089***	6.036***	0.546***
GENOTYPES	99	5.091***	0.272***	1.715***	8.995***	7.324***	0.919*	107.019**	472.992***	0.003**	1093.779***	14.683	62.774***	26.098***	10.568***
LINE	9	13.400***	0.956***	5.140***	17.956***	15.546***	0.854	101.77	1154.345***	0.006**	2348.721***	13.551	77.430*	62.077***	30.405***
TESTER	9	21.983***	1.365***	4.914***	60.193***	42.387***	2.964***	294.119***	1862.039***	0.006**	6076.792***	18.953	191.173***	159.523***	56.892***
LINE:TESTER	81	2.291**	0.075***	0.980***	2.311*	2.515*	0.699	86.814	242.948**	0.003	400.673	14.334	46.879	7.276	3.217***
Residuals	249	1.524	0.042	0.538	1.614	1.734	0.662	69.41	156.768	0.002	356.431	12.24	37.526	7.126	1.363

*-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 5.4 Mean square values for grain yield and other traits at Cedara

Source	DF	GY	EPP	MOI	TL	EH	EPO	PH		SL	SP	ASI	EL
REP	3	3.678***	0.010***	0.451***	0.003	147.954***	0.004***	227.651	0.001***	0.003	11.877	0.080***	0.476***
GENOTYPES	99	2.598**	0.122***	1.445***	0.005	510.855***	0.007***	611.609***	0.123	0.004	24.514	0.196	5.85
LINE	9	7.369***	0.280***	2.390***	0.010*	1025.051***	0.011***	1524.040***	0.021	0.007	26.749	0.149	6.016
TESTER	0	1.233	0.118	0.623	0.003	373.799*	0.004	696.404*	0.007	0.001	24.217	0.063	7.473
LINE:TESTER	81	2.219	0.105*	1.432***	0.005	468.950***	0.007***	500.806**	0.096	0.004	24.299	0.216	5.651
Residuals	251	1.69	0.074	0.647	0.004	183.13	0.003	300.548	0.204	0.004	13.929	0.179	4.921

*-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 5.5 Mean square values for grain yield and other traits at Jozini

Source	DF	GY	EPP	MOI	AD	SD	EH	EPO	PH	ASI	EL
REP	3	0.598**	0.015	0.145**	0.443***	2.070***	108.174***	0.001**	420.716***	2.422***	0.211
GENOTYPES	99	1.598***	0.086***	1.162***	12.224***	15.32***	408.827***	0.004***	582.981***	5.167***	8.907***
LINE	9	3.016***	0.245***	2.108**	31.967***	21.938***	1712.532***	0.018***	1895.320***	18.629***	25.993***
TESTER	9	3.334***	0.301***	3.346***	64.982***	83.254***	1271.173***	0.009***	2236.320***	12.959***	46.536***
LINE:TESTER	81	1.247*	0.045	0.814	4.168***	3.958***	168.155	0.002	253.462*	2.806*	2.827
Residuals	249	0.933	0.034	0.667	2.013	1.924	133.827	0.002	172.034	2.069	2.412

*-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 5.6 Mean square values for grain yield and other traits at Ukulinga

Source	DF	GY	EPP	MOI	AD	SD	TL	ASI	EL
REP	3	1.047**	0.008	6.040***	14.595***	20.986***	399.944***	0.633***	5.836***
GENOTYPES	99	1.904*	0.151***	3.308***	26.032***	26.776***	851.185***	1.001	8.221***
LINE	9	2.129	0.454***	5.537***	46.583***	46.567***	2271.644***	1.999*	16.864***
TESTER	9	9.721***	0.669****	13.803***	201.015***	203.409***	3741.247***	1.770*	44.930***
LINE:TESTER	81	1.011	0.060**	1.894	4.307**	4.951*	372.238	0.805	3.182
Residuals	249	1.446	0.038	1.626	2.659	3.488	320.079	0.864	3.635

*-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 5.7 Line GCA effects for grain yield and other studied traits at Dundee

LINE	GY	EPP	MOI	AD	SD	TL	EH	EPO	PH	RL	SL	SP	ASI	EL
1	-0.414	-0.048	-0.238	-0.956	-0.881	0.179	-5.977	-0.017	-3.963	-0.923	1.148	-0.190	0.057	-0.928
10	-0.767	-0.061	-0.295	-0.134	-0.176	-1.456	-3.250	0.009	-11.389	0.184	-1.701	-1.943	0.032	-0.985
2	0.419	0.201	-0.052	-0.619	-0.559	-0.372	-7.665	-0.002	-13.068	0.272	-0.628	0.200	0.069	-0.059
3	0.033	-0.16	0.206	0.451	0.301	-1.802	4.218	0.009	3.996	0.360	-2.197	0.070	-0.131	0.878
4	-0.423	-0.213	-0.751	-0.469	-0.497	-1.727	5.400	0.017	4.866	-0.579	-1.221	-1.230	-0.053	-1.035
5	-0.092	-0.122	-0.099	1.141	0.811	-0.081	2.230	-0.003	6.423	-0.475	0.307	-1.182	-0.344*	1.288
6	0.173	0.193	0.445	0.479	0.739	1.986	5.618	0.005	8.361	0.421	1.587	1.379	0.209	-0.814
7	0.163	0.047	0.241	-0.310	-0.248	3.070	-2.565	-0.007	-0.916	0.855	2.167	1.563	0.097	0.388
8	-0.563	-0.117	0.465	-0.505	-0.418	0.640	-6.436	-0.022	-2.795	0.716	-0.052	-0.948	0.047	-0.064
9	1.305	0.234	0.115	0.874	0.929	0.126	6.993	0.007	9.626	-0.430	0.572	1.772	0.049	1.084
SE	0.549	0.147	0.34	0.636	0.591	1.513	5.096	0.012	7.270	0.552	1.320	1.182	0.139	0.827
Mean	7.674	1.476	14.008	74.286	74.835	21.940	126.249	0.472	267.664	7.995	13.946	83.267	0.549	20.039

Table 5.8 Line GCA effects for grain yield and other studied traits at Jozini

LINE	GY	MOI	AD	SD	ASI	EL	EPP
1	0.055	-0.166	-0.567	-1.138	-0.586	-1.349	0.032
10	-0.428	-0.114	0.408	0.720	0.324	-0.732	-0.046
2	-0.032	-0.193	0.608	0.307	-0.311	-0.181	0.153
3	0.386	0.009	0.233	-0.776	-1.011	0.645	-0.058
4	0.52	-0.513*	-0.167	-0.498	-0.326	-0.479	0.021
5	-0.158	0.15	0.483	0.689	0.189	1.68	-0.124
6	0.178	0.18	0.982	0.660	-0.317	-0.385	0.078
7	-0.093	0.249	-0.542	-0.307	0.214	-0.024	-0.041
8	-0.297	0.063	-1.867	-0.317	1.549*	0.038	-0.048
9	-0.244	0.279	0.758	1.085	0.339	0.636	0.011
SE	0.26	0.218	0.848	0.703	0.647	0.765	0.074
Mean	5.063	16.416	58.642	59.503	0.861	21.152	1.085

Table 5.9 Line GCA effects for grain yield and other studied traits at Ukulinga

LINE	GY	EPP	MOI	AD	SD	ASI	TL	EH	EPO	PH	EL
1	-0.076	0.080	0.266	-1.575	-2.015	-0.414	-11.657	-5.764	-0.026	2.386	-0.747
10	0.244	-0.023	0.331	0.354	0.329	-0.022	-10.043	-1.955	0.013	-10.764	0.173
2	-0.488	0.136	-0.667	-0.439	-0.377	0.092	7.631	-8.020	-0.024	-3.374	-0.389
3	0.177	-0.191	0.081	0.439	0.198	-0.243	-2.468	5.816	0.027	-1.870	1.170
4	0.003	0.001	-0.301	1.218	1.126	-0.109	-9.574	4.092	0.011	2.868	-0.958
5	0.295	-0.137	-0.058	0.424	0.330	-0.072	-0.046	1.361	-0.011	8.898	0.876
6	-0.032	0.069	0.298	0.661	0.781	0.109	0.553	5.502	0.002	11.289	0.148
7	-0.003	0.000	-0.314	-1.185	-0.902	0.269	6.947	-2.304	0.009	-10.023	-0.136
8	-0.015	-0.101	0.269	-1.482	-1.141	0.349	4.433	-10.002	-0.029	-7.373	-0.055
9	-0.107	0.116	0.462	1.473	1.490	0.028	11.961	9.947	0.029	3.498	-0.053
SE	0.219	0.101	0.353	1.024	1.024	0.212	7.149	6.207	0.020	6.613	0.616
Mean	5.639	1.353	17.377	81.941	81.360	-0.581	78.081	121.367	0.463	262.335	19.172

Table 5.10 Line GCA effects for grain yield and other studied traits at Cedara

LINE	GY	EPP	MOI	TL	EH	EPO	PH	RL	SL	SP	ASI	EL
1	0.5865	0.1741	0.0085	0.010	-8.477	-0.021	-8.469	0.016	-0.006	-0.761	0.1117	0.5073
10	-0.8318	-0.1420	-0.3079	0.031	-5.156	0.013	-13.233	0.013	0.018	0.849	0.0318	-0.2401
2	0.0695	0.0033	0.0960	0.002	-5.177	-0.023	0.531	0.007	-0.005	-0.929	0.0097	0.2501
3	-0.0912	0.0727	-0.0665	-0.027	-2.227	-0.010	-0.369	-0.007	-0.020	-0.669	-0.0657	-0.0911
4	0.5823	0.0283	0.4696	-0.005	4.519	0.015	2.067	-0.006	0.000	1.563	-0.0400	0.3414
5	0.0131	-0.0554	-0.0665	-0.022	2.173	0.018	-5.694	-0.003	-0.020	0.031	-0.0384	-0.0370
6	0.1776	0.0226	0.0310	0.006	-2.777	-0.020	5.131	-0.004	0.010	-0.203	-0.0148	0.3330
7	0.0198	0.0088	-0.0265	-0.003	4.173	0.009	4.381	-0.004	0.001	1.151	-0.0871	-0.6950
8	-0.1547	-0.0807	0.2271	0.000	7.469	0.013	9.317	-0.003	0.003	-0.208	0.0250	0.0950
9	-0.4136	-0.0396	-0.3540	0.014	3.623	0.007	3.806	-0.005	0.019	-0.459	0.0592	-0.3789
SE	0.4072	0.0794	0.2319	0.015	4.802	0.016	5.856	0.007	0.013	0.776	0.0578	0.3679
Mean	6.8657	1.4457	14.1590	0.053	103.177	0.410	251.844	0.008	0.044	81.165	-0.9609	18.9556

Table 5.11 Tester GCA effects for grain yield and other studied traits at Cedara

SITE	TESTER	GY	EPP	MOI	EL	ASI	TL	EH	EPO	PH	RL	SL	SP
	1	0.5865	0.1741	0.0085	0.5073	0.1117	0.012	-1.677	-0.003	-2.119	0.0095*	0.003	0.974
	10	-0.8318	-0.1420	-0.3079	-0.2401	0.0318	-0.013	-0.935	-0.0055	0.178	-0.001	-0.012	-0.223
	2	0.0695	0.0033	0.0960	0.2501	0.0097	-0.013	-5.281	-0.0162	-3.308	-0.0052	-0.008	-0.69
	3	-0.0912	0.0727	-0.0665	-0.0911	-0.0657	0.018	-2.673	-0.0163	2.921	0.0035	0.015*	-0.443
	4	0.5823	0.0283	0.4696	0.3414	-0.0400	-0.002	-0.402	0.0003	-1.569	0.0021	-0.004	1.361
	5	0.0131	-0.0554	-0.0665	-0.0370	-0.0384	0.007	0.473	-0.0059	4.056	0.0003	0.007	-0.14
	6	0.1776	0.0226	0.0310	0.3330	-0.0148	0.004	5.523	0.006	9.181*	0.0003	0.003	0.452
	7	0.0198	0.0088	-0.0265	-0.6950	-0.0871	-0.01	-1.456	0.014	-6.683	-0.0056	-0.005	0.653
	8	-0.1547	-0.0807	0.2271	0.0950	0.0250	-0.004	-0.252	0.0072	-3.444	-0.0024	-0.001	-0.624
	9	-0.4136	-0.0396	-0.3540	-0.3789	0.0592	0.004	4.823	0.0206*	-1.744	0.0023	0.002	-0.956
	SE	0.4072	0.0794	0.2319	0.3679	0.0578	0.008	2.9	0.0092	3.958	0.0041	0.006	0.738
	Mean	6.8657	1.4457	14.1590	18.9556	-0.9609	0.053	103.177	0.4103	251.844	0.0085	0.044	81.165

Table 5.12 Tester GCA effects for grain yield and other studied traits at Dundee

SITE	TESTER	GY	EPP	MOI	EL	AD	SD	ASI	TL	EH	EPO	PH	RL	SL	SP
	1	-0.414	-0.048	-0.238	-0.928	1.201	1.079	0.057	-0.406	7.453	-0.001	15.699	0.266	-0.678	-3.072
	10	-0.767	-0.061	-0.295	-0.985	-0.053	0.156	0.032	-0.936	2.299	-0.023	19.393	0.368	-1.281	0.960
	2	0.419	0.201	-0.052	-0.059	1.497	1.058	0.069	-2.520	-5.195	-0.010	-4.346	-0.234	-2.401	-2.062
	3	0.033	-0.160	0.206	0.878	-0.228	-0.057	-0.131	5.811	-12.728	-0.011	-20.828	1.052	4.681	-2.206
	4	-0.423	-0.213	-0.751	-1.035	0.158	0.322	-0.053	1.553	8.047	0.016	6.985	0.199	1.396	-0.816
	5	-0.092	-0.122	-0.099	1.288	2.081	1.569	-0.344*	-2.128	4.526	0.005	5.364	-0.416	-1.695	-0.840
	6	0.173	0.193	0.445	-0.814	-1.596	-1.394	0.209	-4.128	-8.968	-0.005	-15.494	-1.146	-3.013	0.760
	7	0.163	0.047	0.241	0.388	-0.667	-0.529	0.097	2.413	0.477	0.021	-9.153	0.511	1.833	2.401
	8	-0.563	-0.117	0.465	-0.064	-0.570	-0.534	0.047	-0.792	-3.858	-0.010	-3.598	-0.895	0.177	2.124
	9	1.305	0.234	0.115	1.084	-1.873	-1.669	0.049	1.696	6.513	0.012	7.119	0.696	0.962	2.243
	SE	0.549	0.147	0.340	0.827	1.164	0.977	0.139	2.572	6.473	0.012	11.693	0.653	2.074	1.895
	Mean	7.674	1.476	14.008	20.039	74.286	74.835	0.549	21.940	126.249	0.472	267.664	7.995	13.946	83.267

Table 5.13 Tester GCA effects for grain yield and other studied traits at Ukulinga

SITE	TESTER	GY	EPP	MOI	EL	AD	SD	ASI	TL
	1	-0.076	0.080	0.266	-0.747	3.157	2.977	-0.414	2.97
	10	0.244	-0.023	0.331	0.173	-0.697	-0.281	-0.022	-0.267
	2	-0.488	0.136	-0.667	-0.389	1.982	1.988	0.092	-9.15
	3	0.177	-0.191	0.081	1.170	-0.291	-0.475	-0.243	17.093
	4	0.003	0.001	-0.301	-0.958	0.839	0.953	-0.109	3.465
	5	0.295	-0.137	-0.058	0.876	3.588	3.681	-0.072	-9.313
	6	-0.032	0.069	0.298	0.148	-2.51	-2.523	0.109	-21.302*
	7	-0.003	0.000	-0.314	-0.136	-1.45	-1.779	0.269	6.246
	8	-0.015	-0.101	0.269	-0.055	-1.583	-1.711	0.349	4.759
	9	-0.107	0.116	0.462	-0.053	-3.146	-3.011	0.028	3.234
	SE	0.219	0.101	0.353	0.616	2.213	2.193	0.212	9.175
	Mean	5.639	1.353	17.377	19.172	81.941	81.36	-0.581	78.081

Table 5.14 Tester GCA effects for grain yield and other studied traits at Jozini

SITE	TESTER	GY	EPP	MOI	EL	AD	SD	ASI	EH	EPO	PH
	1	0.055	0.032	-0.166	-1.349	0.531	0.28	-0.586	0.812	-0.012	8.009
	10	-0.428	-0.046	-0.114	-0.732	0.833	1.393	0.324	-3.377	-0.022	5.937
	2	-0.032	0.153	-0.193	-0.181	0.759	0.976	-0.311	-2.229	-0.006	-0.884
	3	0.386	-0.058	0.009	0.645	-0.492	-1.435	-1.011	-8.369	-0.007	-14.575
	4	0.52	0.021	-0.513*	-0.479	0.158	0.378	-0.326	3.303	0.006	1.639
	5	-0.158	-0.124	0.15	1.68	2.658	3.066	0.189	10.237	0.024	8.322
	6	0.178	0.078	0.18	-0.385	-1.967	-1.115	-0.317	-8.312	-0.013	-10.099
	7	-0.093	-0.041	0.249	-0.024	-0.242	-1.021	0.214	3.548	0.02	-2.8
	8	-0.297	-0.048	0.063	0.038	-0.517	-0.299	1.549*	-0.038	0.007	-3.75
	9	-0.244	0.011	0.279	0.636	-1.392	-1.802	0.339	3.099	0.006	3.738
	SE	0.26	0.074	0.218	0.765	1.209	1.369	0.647	5.348	0.014	7.093
	Mean	5.063	1.085	16.416	21.152	58.642	59.503	0.861	121.367	0.463	262.335

Table 5.15 SCA effects for grain yield and other traits at Cedara

LINE	TESTER	GY	TL	EH	EPO	PH	RL	SL	SP	EL	EPP	MOI	EH	EPO	PH	AD	SD	ASI
3	5	-2.518***	-0.032	-26.923*	-0.088*	-13.781	-0.0017	-0.03	0.155	-0.257	0.633***	-1.024	-0.158	0.0167	-9.218	-0.783	-0.819	-0.436
10	2	2.135*	-0.035	-13.03	-0.079	7.305	0.0169	-0.052	-2.319	2.285	0.201	1.225	-1.504	0.0304	-16.465	-0.809	0.841	-0.078
3	7	1.700*	0.029	5.506	-0.001	8.208	0.0041	0.025	0.061	-0.413	0.051	0.483	7.433	0.0158	6.523	-1.383	-1.906	0.047
3	8	1.607*	0.008	19.802	0.046	18.219	0.001	0.007	-1.704	1.115	-0.059	0.499	-6.362	-0.02	-1.579	-0.358	-0.007	0.514*
5	8	1.46	-0.011	0.652	-0.012	6.544	0.0112	-0.023	2.197	-2.429*	0.345*	-0.076	0.744	0.0038	-0.664	1.142	1.126	-0.015
8	5	1.288	0.011	3.881	0.004	8.283	0.0218	-0.011	-2.288	-0.057	0.153	0.883	2.605	-0.0067	12.084	0.567	-1.248	-0.029
4	6	1.173	0.008	-12.219	-0.033	-9.842	0.0114	-0.004	3.216	0.309	-0.048	0.275	3.012	0.0214	-5.394	1.992	0.589	-0.007
6	4	1.072	-0.01	-20.248	-0.057	-15.906	-0.0066	-0.003	-1.403	-0.344	0.235	0.174	-14.399	-0.0503*	-0.889	-0.782	-0.283	-0.063
9	1	1.032	-0.018	12.127	0.034	8.219	-0.0126	-0.005	-1.22	0.748	0.091	0.234	1.019	0.0181	-15.44	0.319	2.031*	-0.154
6	3	1.017	0.021	12.023	0.035	8.354	-0.008	0.029	-3.097	0.663	0.148	0.98	-1.434	0.0315	-19.671*	-0.132	-0.228	0.012
8	10	-0.832	-0.005	17.999	0.052	9.769	-0.0053	0	0.031	-0.661	-0.232	-0.001	11.836	0.0604	-7.266	3.892**	3.627*	-0.021
9	3	-0.891	-0.068	18.623	0.061	7.179	-0.0066	-0.061	-0.083	0.882	-0.179	-0.11	3.572	0.0076	4.207	1.092	0.838	-0.072
2	2	-0.895	0.035	-9.719	-0.033	-3.567	-0.01	0.045	1.071	0.298	-0.244	0.36	-2.207	0.0014	-6.088	-0.009	0.864	-0.036
2	7	-0.901	-0.014	-7.544	-0.017	-14.692	-0.0096	-0.004	-1.014	-0.649	0.137	-0.555	-1.723	0.0122	-9.151	1.742	0.167	-0.042
5	1	-1.034	-0.013	-3.173	-0.015	0.719	-0.0008	-0.012	-0.103	0.512	-0.153	-0.029	5.61	0.0122	3.802	1.094	0.967	-0.057
8	7	-1.047	0.034	-4.44	-0.043	10.772	-0.0002	0.034	0.267	1.655	-0.078	-0.461	4.078	0.0259	-5.215	-0.783	0.517	-0.053
9	6	-1.084	0.048	0.927	0.013	-6.581	-0.0035	0.051	-0.136	-0.241	-0.097	0.074	-12.502	-0.0256	-11.421	-0.183	0.305	0.386
6	1	-1.117	0.02	-0.473	0.015	-9.856	0.0007	0.02	-2.19	1.262	-0.097	-0.601	9.092	0.0307	1.357	-0.174	-0.568	-0.078
6	9	-1.207	0.042	-2.973	-0.013	1.269	-0.0069	0.049	-0.662	-1.396	-0.104	-0.579	10.385	0.0251	9.255	0.768	0.646	-0.338
4	2	-1.258	-0.005	-1.915	0.018	-13.853	0.0022	-0.008	1.15	0.225	-0.082	-0.913	9.159	0.0146	10.998	-1.734	-1.389	0.022
SE		0.741	0.036	10.773	0.042	11.133	0.0171	0.031	2.452	1.183	0.161	0.595	6.451	0.022	7.92	1.016	0.99	0.231
Mean		6.866	0.053	103.177	0.41	251.844	0.0085	0.044	81.165	18.956	1.446	14.159	121.367	0.4626	262.335	58.642	59.503	-0.961

*-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 5.16 SCA effects for grain yield and other traits at Dundee

LINE	TESTER	GY	AD	SD	TL	EH	EPO	PH	RL	SL	SP	MOI	EL	EPP	ASI
10	10	-1.973*	0.265	0.317	5.069	3.421	0.026	-9.565	0.836	4.21	0.045	-0.404	-1.344	-0.066	0.105
4	4	-1.813*	1.472	1.107	6.116	-18.977*	-0.049	-17.145	1.654	4.487	-1.6	-0.761	-0.25	-0.256	-0.276
6	2	1.537*	-1.005	-0.918	-0.155	0.876	0.003	0.279	0.63	-0.811	0.696	0.646	0.139	0.234	0.025
10	3	1.506	0.367	-0.754	-4.074	0.712	-0.026	14.746	-1.945	-2.385	-2.759	0.032	0.856	0.22	-0.946
5	6	1.348	-0.789	-0.191	-1.597	8.173	0.007	8.702	0.724	-2.182	2.042	-0.007	2.161*	0.08	0.455
7	1	1.348	-0.338	-0.315	-6.164	2.867	-0.001	6.877	-0.13	-6.206	0.629	0.188	0.2	0.291	0.167
8	10	1.172	0.114	0.348	5.702	15.103	0.018	26.591	1.412	4.362	-0.156	0.72	0.348	0.138	0.223
10	1	1.171	-0.79	-0.699	-1.26	7.756	0.03	-0.85	-2.076	1.195	3.088*	-0.223	1.328	-0.038	0.064
3	10	1.109	-0.019	-0.064	2.592	-4.822	-0.005	-5.362	1.22	1.365	0.042	-0.315	0.557	0.099	0.034
10	4	1.103	0.129	0.358	-4.328	0.27	-0.008	3.486	-1.635	-2.518	-2.112	0.924	0.175	0.300*	0.161
9	6	-0.763	-0.297	-0.603	-1.13	1.689	0.002	4.4	0.094	-1.068	-0.883	-0.381	0.081	-0.341*	-0.157
1	7	-0.77	0.134	-0.029	2.353	-10.886	-0.043	-2.486	-0.526	2.965	1.029	0.725	-0.383	-0.139	-0.199
3	5	-0.795	-0.159	-0.337	6.512	2.936	0.019	-4.181	1.495	5.161	-0.684	-0.316	-0.66	0.191	-0.147
7	4	-0.821	0.175	0.767	5.217	-7.767	-0.013	-11.839	1.855	3.33	0.094	-0.45	-0.762	-0.075	0.457
9	10	-0.844	-0.868	-0.722	-2.968	-16.064*	-0.024	-21.470*	-1.447	-1.551	-0.789	-0.533	0.58	-0.177	0.123
10	7	-1.063	0.248	1.612	12.811	4.285	0.012	2.235	8.815**	3.728	-1.188	-0.225	-0.729	-0.212	1.330*
6	9	-1.107	1.135	1.730*	-3.212	-0.416	0	-1.186	0.449	-3.579	-0.507	-0.994*	-0.747	-0.103	0.592
2	3	-1.297	0.203	0.763	6.21	-4.285	-0.013	-11.727	1.437	4.709	2.051	0.347	-0.825	-0.07	0.484
5	1	-1.343	0.388	-0.048	2.219	-2.386	-0.008	-1.871	-0.133	2.397	-0.628	-0.4	-0.773	-0.193	-0.362
2	6	-1.379	0.964	1.253	0.521	-7.776	0.02	-21.163*	0.371	0.302	-0.854	0.172	-0.326	-0.157	0.22
SE		0.753	0.756	0.789	4.635	7.754	0.027	9.958	1.884	3.406	1.342	0.492	0.892	0.136	0.416
Mean		7.674	74.286	74.835	21.94	126.249	0.472	267.664	7.995	13.946	83.267	14.008	20.039	1.476	0.549

*-significant at 5% probability level, ** -significant at 1% probability level

Table 5.17 SCA effects for grain yield and other traits at Jozini

SITE	LINE	TESTER	GY	MOI	EL	EPP	EH	EPO	PH	AD	SD	ASI
	1	5	1.649**	-0.042	0.839	0.074	7.816	0.0162	7.816	-0.233	-1	-0.689
	3	5	-1.269*	-0.126	-1.028	-0.282**	-0.158	0.0167	-9.218	-0.783	-0.819	-0.014
	10	9	1.138*	-0.449	-0.12	0.156	9.741	0.0186	7.595	0.842	-0.067	-0.799
	1	3	1.116*	-0.548	-0.978	0.197	-0.105	-0.0069	2.174	-0.333	-0.412	-0.079
	4	2	0.973	-0.183	-0.534	0.103	9.159	0.0146	10.998	-1.734	-1.389	0.239
	2	10	0.954	1.085*	0.918	0.018	0.795	-0.0117	7.81	0.667	-0.195	-0.859
	3	6	0.942	0.955*	0.509	0.099	4.155	0.0029	8.841	1.092	0.459	-0.664
	1	4	0.877	0.443	0.339	0.095	2.22	-0.0052	11.435	0.267	0.358	0.011
	9	7	0.772	-0.375	-0.856	0.087	-6.611	-0.0089	-6.711	-0.158	-0.551	-0.399
	8	1	0.735	0.609	1.673*	-0.049	8.261	0.0201	11.428	0.194	-1.049	-1.166
	1	6	-0.724	0.583	0.03	-0.08	-8.493	-0.0138	-13.272	-0.358	0.471	0.911
	4	5	-0.761	0.086	0.965	0.028	6.594	0.0249	-1.434	1.367	1.922	0.551
	10	1	-0.787	-0.252	-0.125	-0.239*	-5.728	-0.0219	-1.065	-0.081	-0.448	-0.441
	8	6	-0.858	-0.274	-1.549	0.043	-12.761	-0.0377	-6.38	-0.558	1.207	1.776*
	3	9	-0.897	0.333	-0.859	-0.091	-1.975	0.0172	-13.834	0.017	0.518	0.536
	1	2	-0.923	0.107	0.653	-0.187	-6.372	-0.0247	-1.26	1.666	0.429	-1.251
	1	8	-0.951	-0.079	-0.407	-0.092	-0.722	0.0198	-12.959	-0.058	0.113	0.261
	2	7	-0.951	-0.712	-0.123	-0.163	-1.723	0.0122	-9.151	1.742	0.167	-1.499
	4	3	-1.052	0.352	0.014	0.011	-5.508	-0.0255	1.95	-0.733	0.435	1.161
	8	10	-1.056	0.329	-0.471	-0.023	11.836	0.0604	-7.266	3.892**	3.627*	-0.368
	SE		0.556	0.449	0.836	0.105	6.451	0.022	7.92	1.016	0.99	0.833
	Mean		5.063	16.416	21.152	1.085	121.367	0.4626	262.335	58.642	59.503	0.861

*-significant at 5% probability level, ** -significant at 1% probability level

Table 5.18 SCA effects for grain yield and other traits at Ukulinga

SITE	LINE	TESTER	GY	MOI	EL	EPP	ASI	AD	SD	TL
	4	3	1.094*	-0.063	2.092*	0.330**	-0.138	-1.87	-1.956	-6.159
	5	10	-1.083*	0.942	-0.745	-0.035	0.24	-1.029	-0.72	4.204
	1	10	-1.005*	0.147	-0.613	-0.03	-0.65	0.46	-0.245	11.288
	5	9	1.158	0.066	0.682	-0.026	0.761	-0.253	0.598	-20.254*
	8	10	0.949	2.039*	-0.346	0.273	-0.388	-0.31	-0.71	-14.583
	1	5	0.94	-0.708	-0.044	0.064	-0.038	-1.362	-1.351	-4.135
	3	5	0.894	-0.716	1.019	0.132	-0.284	-1.724	-2.025	12.945
	9	4	0.79	-0.102	0.059	0.141	-0.158	-0.001	-0.201	-1.076
	6	7	0.774	-0.194	-0.166	0.12	-0.098	-0.574	-0.698	6.529
	2	4	0.743	-0.177	1.62	0.204	-0.666	-0.159	-0.739	4.595
	1	1	-0.555	0.885	-0.773	0.11	-0.009	0.348	0.327	1.45
	9	5	-0.567	-0.082	-0.759	-0.09	-0.583	-1.151	-1.729	7.777
	6	9	-0.594	-0.174	0.423	0.06	0.299	-0.641	-0.319	2.618
	8	1	-0.609	-0.456	1.031	-0.009	0.526	1.524	2.006	7.267
	10	5	-0.662	0.666	-0.796	0.202	-0.051	0.073	-0.024	8.475
	4	5	-0.708	0.701	-0.924	-0.163	0.666	1.928	2.633*	-7.362
	8	8	-0.737	0.098	-0.291	-0.213	0.462	-1.975	-1.484	5.206
	4	9	-0.811	-0.3	0.952	-0.204	0.564	-0.178	0.341	11.241
	4	4	-0.878	0.085	-0.781	-0.277*	-0.371	0.768	0.378	6.836
	2	8	-0.885	0.39	0.565	-0.173	-0.412	-0.241	-0.58	-0.253
	SE		0.5	0.685	0.887	0.121	0.446	1.032	1.107	9.598
	Mean		5.639	17.377	19.172	1.353	-0.581	81.941	81.36	78.081

*-significant at 5% probability level

Table 5.19 Variance components and heritability estimates at Cedara

SITE	GY	EH	EPO	PH	RL	SL	SP	TL	ASI	EL	EPP	MOI
Line Variance	0.1321	14.2590	0.00010	26.2368	0.00003	0.00009	0.06283	0.00013	0.00000	0.0094	0.0045	0.0246
Tester Variance	0.0000	0.0000	0.00000	5.0154	0.00000	0.00000	0.00000	0.00000	0.00000	0.0467	0.0003	0.0000
Line x Tester Variance	0.1356	73.2873	0.00113	51.3481	0.00010	0.00005	2.65893	0.00025	0.00971	0.1872	0.0079	0.2013
Genotype Variance	0.0534	5.9096	0.00001	15.6261	0.00001	0.00001	0.03037	0.00004	0.00000	0.0280	0.0024	0.0019
Additive Variance	0.2135	23.6384	0.00003	62.5043	0.00003	0.00005	0.12149	0.00014	0.00000	0.1121	0.0097	0.0077
Dominance Variance	0.5423	293.1492	0.00451	205.3924	0.00038	0.00018	10.63571	0.00100	0.03886	0.7487	0.0316	0.8051
Environmental Variance	0.4226	45.7825	0.00069	75.1370	0.00020	0.00093	3.48218	0.00103	0.04468	1.2302	0.0186	0.1617
Broad Heritability	0.6414	0.8737	0.86864	0.7810	0.67221	0.20225	0.75545	0.52644	0.46517	0.4117	0.6898	0.8341
Narrow Heritability	0.1812	0.0652	0.00649	0.1822	0.05479	0.04432	0.00853	0.06602	0.00000	0.0536	0.1618	0.0079

Table 5.20 Variance components and heritability estimates at Dundee

SITE	GY	AD	EH	EPO	PH	RL	SD	SL	SP	TL	ASI	EL	EPP	MOI
Line Variance	0.2848	0.4032	23.3692	0.0001	49.9499	0.0000	0.3359	0.7834	1.4070	0.3835	0.0040	0.6971	0.0227	0.1067
Tester Variance	0.5049	1.4918	41.5152	0.0001	145.5415	0.1184	1.0277	3.6998	3.9088	5.3155	0.0587	1.3763	0.0332	0.1009
Line x Tester Variance	0.1966	0.1796	22.0975	0.0002	11.3442	0.5369	0.2012	2.3982	0.0384	4.4624	0.0097	0.4753	0.0083	0.1132
Genotype Variance	0.3949	0.9421	32.4422	0.0001	97.7457	0.0492	0.6779	2.2416	2.6541	2.8495	0.0310	1.0367	0.0278	0.1038
Additive Variance	1.5795	3.7685	129.7687	0.0004	390.9829	0.1967	2.7115	8.9664	10.6164	11.3980	0.1239	4.1468	0.1113	0.4151
Dominance Variance	0.7864	0.7185	88.3901	0.0007	45.3768	2.1476	0.8047	9.5927	0.1534	17.8495	0.0388	1.9014	0.0334	0.4527
Environmental Variance	0.3811	0.4034	39.1919	0.0005	89.1077	3.0601	0.4335	9.3815	1.7816	17.3526	0.1655	0.3408	0.0105	0.1345
Broad Heritability	0.8613	0.9175	0.8477	0.6601	0.8304	0.4338	0.8902	0.6642	0.8581	0.6276	0.4957	0.9467	0.9322	0.8658
Narrow Heritability	0.5750	0.7706	0.5042	0.2237	0.7441	0.0364	0.6865	0.3209	0.8458	0.2446	0.3775	0.6491	0.7171	0.4141

Table 5.21 Variance components and heritability estimates at Jozini

SITE	GY	AD	EH	EPO	PH	SD	ASI	EL	EPP	MOI
Line Variance	0.045	0.716	39.599	0.00040	42.171	0.463	0.409	0.594	0.005	0.033
Tester Variance	0.054	1.567	28.283	0.00018	50.930	2.044	0.263	1.121	0.007	0.065
Line x Tester Variance	0.080	0.556	8.802	0.00003	20.915	0.524	0.191	0.106	0.003	0.038
Genotype Variance	0.049	1.135	33.941	0.00029	46.462	1.246	0.333	0.857	0.006	0.049
Additive Variance	0.198	4.542	135.764	0.00116	185.848	4.986	1.331	3.429	0.023	0.196
Dominance Variance	0.322	2.222	35.208	0.00012	83.659	2.097	0.762	0.425	0.011	0.151
Environmental Variance	0.233	0.503	33.457	0.00046	43.008	0.481	0.517	0.603	0.008	0.167
Broad Heritability	0.690	0.931	0.836	0.73577	0.862	0.936	0.802	0.865	0.804	0.676
Narrow Heritability	0.263	0.625	0.664	0.66795	0.595	0.659	0.510	0.769	0.543	0.382

Table 5.22 Variance components and heritability estimates at Ukulinga

SITE	GY	AD	SD	TL	ASI	EL	EPP	MOI
Line Variance	0.029	1.089	1.072	48.744	0.031	0.351	0.010	0.093
Tester Variance	0.223	5.065	5.111	86.459	0.025	1.071	0.016	0.306
Line x Tester Variance	0.000	0.424	0.377	13.386	0.000	0.000	0.006	0.069
Genotype Variance	0.126	3.071	3.085	67.730	0.028	0.713	0.013	0.200
Additive Variance	0.505	12.285	12.341	270.921	0.111	2.850	0.052	0.800
Dominance Variance	0.000	1.698	1.507	53.543	0.000	0.000	0.022	0.275
Environmental Variance	0.361	0.665	0.872	80.020	0.216	0.909	0.009	0.406
Broad Heritability	0.583	0.955	0.941	0.802	0.339	0.758	0.887	0.726
Narrow Heritability	0.583	0.839	0.838	0.670	0.339	0.758	0.618	0.540

Table 5.23 Mean square values for GY, EPP, EL, MOI and ASI across four sites

Source	DF	GY	EPP	EL	MOI	ASI
SITE	3	236.864	7.138	232.994	726.068	225.89
REP(SITE)	12	2.308	0.022	2.19	2.686***	0.97
GENOTYPES	99	3.185***	0.287	16.935	2.56***	1.916***
LINE	9	4.867***	1.067	39.447	4.397***	7.965***
TESTER	9	14.068***	1.428	105.963	9.244***	5.336***
LINE:TESTER	81	1.793	0.073**	4.547**	1.621***	0.866
SITE:GENOTYPES	297	2.679***	0.112	5.443***	1.683***	1.754***
SITE:LINE	27	7.089***	0.289	13.409***	3.585***	4.460***
SITE:TESTER	27	7.266***	0.331	16.196***	4.357***	4.038***
SITE:LINE:TESTER	243	1.679*	0.068***	3.364	1.174**	1.199**
Residuals	992	1.398	0.047	3.085	0.873	0.946

*-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 5.24 Mean square values for RL, SL and SP across two sites

Source	Df	RL	SL	SP
SITE	1	12436.897***	23251.793***	694.455***
REP(SITE)	6	3.306	58.982**	9.363
GENOTYPES	99	7.351	31.099***	22.197***
LINE	9	6.694	39.111*	34.821***
TESTER	9	9.487	95.297***	76.329***
LINE:TESTER	81	7.142	23.113	14.800*
SITE:GENOTYPES	99	7.367	31.639***	28.083***
SITE:LINE	9	6.854	39.440*	52.640***
SITE:TESTER	9	9.445	97.580***	103.903***
SITE:LINE:TESTER	81	7.193	23.445	16.930**
Residuals	502	6.121	18.768	10.577

*-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 5.25 Mean square values for AD, SD, TL, EH, EPO and PH across three sites

Source	Df	AD	SD	TL	EH	EPO	PH
SITE	2	20080.092***	20439.395***	227543.927***	34754.618***	0.324***	13093.962***
REP(SITE)	9	5.967**	9.137***	180.088	54.8	0.002	344.623
GENOTYPES	99	36.643***	35.109***	366.625***	683.800***	0.007***	1023.458***
LINE	9	69.277***	62.065***	953.160***	2632.607***	0.021***	3239.505***
TESTER	9	282.397***	275.415***	1911.610***	1924.343***	0.012***	4533.984***
LINE:TESTER	81	5.698***	5.395***	130.058	329.070***	0.005***	387.330*
SITE:GENOTYPES	198	5.029***	5.751***	295.580***	362.066***	0.004***	619.006***
SITE:LINE	18	12.321***	9.760***	742.834***	636.492***	0.007***	1237.388***
SITE:TESTER	18	20.864***	26.631***	1067.774***	757.068***	0.004	2146.931***
SITE:LINE:TESTER	162	2.46	2.986*	160.086*	287.685***	0.004***	380.528**
Residuals	747	2.103	2.383	129.544	159.809	0.002	278.644

*-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 5.26 Line GCA effects for grain yield and other studied traits across sites

LINE	GY	EPP	MOI	SP	AD	SD	ASI	TL	EH	EPO	PH	RL	SL	EL
1	0.038	0.06	-0.035	-0.458	-1.031	-1.344	-0.206	-3.757	-6.763	-0.021	-3.372	-0.454	0.571	-0.624
10	-0.436*	-0.065	-0.093	-0.576	0.189	0.271	0.091	-3.774	-3.342	0.012	-11.888	0.098	-0.841	-0.432
2	-0.015	0.119	-0.206	-0.329	-0.161	-0.212	-0.03	2.509	-7.067	-0.016	-5.417	0.139	-0.318	-0.1
3	0.115	-0.083	0.059	-0.298	0.360	-0.103	-0.365	-1.416	2.553	0.008	0.644	0.177	-1.108	0.635
4	0.184	-0.04	-0.268	0.176	0.200	0.034	-0.137	-3.723	4.834	0.014	3.282	-0.292	-0.610	-0.543
5	0.003	-0.111	-0.017	-0.582	0.681	0.608	-0.06	-0.033	1.824	0.002	3.205	-0.239	0.143	0.936
6	0.12	0.087	0.239	0.581	0.683	0.718	-0.004	0.925	2.782	-0.005	8.356	0.209	0.799	-0.187
7	0.033	0.008	0.042	1.362	-0.697	-0.498	0.125	3.460	-0.106	0.004	-2.300	0.425	1.083	-0.11
8	-0.265	-0.087	0.26	-0.585	-1.291	-0.627	0.494*	1.734	-3.310	-0.013	-0.576	0.357	-0.025	0.011
9	0.128	0.079	0.127	0.666	1.014	1.159	0.118	4.019	6.777	0.015	5.522	-0.218	0.296	0.33
SE	0.165	0.077	0.157	0.626	0.721	0.682	0.212	2.674	4.443	0.013	4.950	0.274	0.663	0.471
Mean	6.311	1.34	15.489	82.215	71.632	71.907	-0.031	33.320	116.931	0.448	260.611	4.002	6.995	19.83

Table 5.27 Tester GCA effects for grain yield and other studied traits

TESTER	GY	EPP	MOI	SP	AD	SD	ASI	TL	EH	EPO	PH	RL	SL	EL
1	-0.003	0.058	0.11	-1.07	1.621	1.45	-0.119	0.941	1.943	-0.005	6.8	0.138	-0.338	0.244
10	0.287	-0.152	0.373	0.387	0.009	0.415	0.295	-0.421	-0.584	-0.017	8.532	0.184	-0.646	1.17
2	-0.085	-0.046	-0.003	-1.361	1.41	1.333	-0.067	-3.781	-4.232	-0.011	-2.987	-0.12	-1.206	0.34
3	-0.641*	0.086	-0.277	-1.34	-0.371	-0.665	-0.235	7.751	-7.978	-0.011	-11.179	0.528	2.347	-1.351
4	0.239	0.008	0.197	0.276	0.355	0.54	0.157	1.582	3.534	0.008	2.064	0.1	0.696	0.634
5	0.157	0.017	0.277	-0.473	2.764	2.757	-0.018	-3.732	5.135	0.008	6.061	-0.208	-0.844	0.81
6	-0.376	-0.162	-0.455	0.621	-2.002	-1.67	0.246	-8.416*	-3.991	-0.004	-5.622	-0.573	-1.505	0.16
7	-0.165	-0.046	-0.138	1.557	-0.783	-1.115	-0.265	3.012	1.018	0.018	-5.926	0.253	0.915	-0.2
8	0.194	0.123	-0.051	0.729	-0.89	-0.854	0.037	1.329	-1.45	0.001	-3.351	-0.449	0.088	-1.014
9	0.294	0.082	0.075	0.631	-2.168	-2.184	-0.003	1.681	4.785	0.013	3.066	0.349	0.482	-0.878
SE	0.281	0.09	0.228	0.927	1.455	1.437	0.174	3.786	3.799	0.01	5.831	0.327	1.035	0.772
Mean	6.311	1.34	15.489	82.215	71.632	71.907	-0.031	33.32	116.931	0.448	260.611	4.002	6.995	19.83

Table 5.28 SCA effects for grain yield and other studied traits across sites

TESTER	LINE	GY	EPP	MOI	AD	SD	ASI	TL	EH	EPO	PH	RL	SL	SP	EL
5	1	1.009***	0.06	-0.457	-0.53	-0.53	-0.244	-3.285	4.725	0.01	4.342	-0.242	-2.709	1.462	0.311
5	3	-0.929**	0.173**	-0.564*	-0.867	-0.867	-0.221	6.420*	-8.475	-0.018	-9.387	0.747	2.564	-0.213	-0.221
9	6	-0.784**	-0.018	-0.348	0.495	0.495	0.1	-0.345	2.468	0.002	3.787	0.221	-1.766	-0.596	-0.425
6	5	0.658*	0.028	0.313	-0.582	-0.582	0.19	3.878	2.176	-0.002	4.793	0.359	-1.083	-0.24	0.684
4	4	-0.657*	-0.175**	0.103	0.683	0.683	-0.369	4.234	-6.545	-0.025	-0.564	0.824	2.232	-2.393	-0.382
7	6	0.591	0.036	0.043	0.016	0.016	0.09	1.224	4.498	0	7.267	-0.741	-0.851	1.977	0.448
8	5	0.582	0.107	-0.149	1.269*	1.269*	-0.077	-1.502	-0.272	-0.006	2.331	-0.116	-3.325	1.003	-0.769
1	7	0.483	0.132*	1.030***	0.551	0.551	0.207	-4.151	-0.352	-0.011	5.971	-0.064	-3.127	-0.036	-0.293
2	10	0.475	0.028	0.776	-0.741	-0.741	0.371	5.116	-8.237	-0.031	-3.965	-0.582	-1.35	-0.443	-0.032
7	9	0.41	0.099	0.127	-0.68	-0.68	-0.327	0.68	0.685	-0.009	3.56	1.781*	3.930*	-0.803	-0.419
5	10	-0.34	0.025	0.254	-0.36	-0.36	0.281	2.193	3.456	0	6.308	-0.829	0.114	-0.589	-0.458
7	2	-0.349	-0.061	-0.402	1.332*	1.332	-0.427*	1.131	-0.529	0.028	-12.987*	-0.516	-1.16	-0.605	-0.309
8	7	-0.361	-0.073	-0.124	1.066	1.066	-0.559**	0.895	1.249	-0.004	4.335	-0.36	0.944	1.391	0.346
7	1	-0.37	-0.082	0.539	-0.009	-0.009	0.265	-2.409	-3.316	-0.027	7.081	-0.265	1.49	0.118	0.433
10	5	-0.383	0.042	0.392	-0.637	-0.637	0.045	2.245	4.819	0.004	9.457	0.198	1.101	2.38	-0.306
10	10	-0.403	-0.007	-0.529	0.133	0.133	0.139	-0.925	-1.193	-0.008	-1.471	0.408	2.103	-1.169	-0.771
9	3	-0.404	-0.116	0.248	0.036	0.036	0.027	0.186	7.108	0.03	0.028	1.276	0.989	-0.93	-0.033
3	2	-0.42	-0.023	0.18	0.495	0.495	-0.011	-0.478	-2.851	-0.011	-2.911	0.709	2.385	2.125	-0.358
1	5	-0.437	-0.097	-0.245	0.806	0.806	-0.2	4.057	-0.101	-0.002	0.648	-0.067	1.191	-0.232	-0.141
8	8	-0.492	-0.11	-0.071	-0.793	-0.793	0.071	0.951	-2.67	-0.008	-1.024	-0.117	-1.204	1.234	-0.068
SE		0.301	0.061	0.286	0.62	0.62	0.209	2.963	4.713	0.018	5.113	0.85	1.53	1.224	0.48
Mean		6.311	1.34	15.489	71.632	71.632	-0.031	33.32	116.931	0.448	260.611	4.002	6.995	82.215	19.83

*-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 5.29 Variance components and heritability estimates for grain yield and other traits across sites

	GY	EPP	MOI	SP	AD	SD	ASI	TL	EH	EPO	PH	RL	SL	EL
Line Variance	0.020	0.006	0.018	0.257	0.546	0.486	0.046	7.041	19.688	0.000	24.419	0.000	0.205	0.224
Tester Variance	0.079	0.009	0.049	0.790	2.375	2.318	0.029	15.240	13.635	0.000	35.502	0.030	0.925	0.651
LinexTester Variance	0.025	0.002	0.048	0.542	0.309	0.258	0.000	0.044	14.467	0.000	9.305	0.131	0.557	0.094
Genotype Variance	0.049	0.008	0.033	0.523	1.455	1.397	0.037	11.141	16.662	0.000	29.904	0.012	0.565	0.437
Additive Variance	0.197	0.030	0.133	2.091	5.819	5.587	0.148	44.562	66.646	0.000	119.615	0.049	2.261	1.749
Dominance Variance	0.101	0.007	0.192	2.169	1.234	1.034	0.000	0.176	57.867	0.001	37.221	0.524	2.228	0.375
Baker's ratio	0.661	0.816	0.410	0.491	0.825	0.844	1.000	0.996	0.535	0.330	0.763	0.085	0.504	0.823
Environmental Variance	1.718	0.063	1.075	29.907	3.779	4.300	1.148	228.071	280.498	0.004	484.980	12.864	43.972	3.674
Broad Sense Heritability	0.148	0.369	0.232	0.125	0.651	0.606	0.114	0.164	0.307	0.256	0.244	0.043	0.093	0.366
Narrow sense Heritability	0.098	0.301	0.095	0.061	0.537	0.512	0.114	0.163	0.165	0.084	0.186	0.004	0.047	0.302

5.6 Discussion

Bio-fortification of maize to improve its PVA content is a key task in sub-Saharan Africa (Gregorio, 2002). However, critical genetic information must be derived from the germplasm to be used. In the current study, there was a lot of genetic variation that was created by mating a set of 10 lines with a set of 10 testers derived from different germplasm sources. Such variation offers an excellent opportunity to select desirable lines and testers based on their general combining ability (GCA) effects (Hallauer *et al*., 2010; Gasura *et al*., 2013). Furthermore, it also allows the selection of suitable hybrids based on their desirable SCA effects and *per se* grain yield performance (Pswarayi and Vivek, 2008; Derera *et al*., 2007). The lines and testers that showed positive GCA effects for grain yield and other desirable GCA effects for various traits were identified as lines 1, 5 and 6 and tester 5, 6 and 7. These maize inbreds lines are suitable candidates for use in future breeding activities that are aimed at improving the grain yield and other allied traits performance of the PVA hybrids.

Suitable hybrids are normally obtained when diverse germplasm is used (Amiruzzaman *et al*., 2013). In this study, the occurrence of significant SCA interactions for grain yield indicated that the hybrids were developed using inbred lines from diverse sources. Interesting suitable testers came from the PVA group as well as from normal maize. Some desirable normal maize testers would thus be required to be converted to PVA maize.

The Baker's ratio was above 50% for most traits such as grain yield and this indicated that additive gene action were more important in controlling gene action in PVA maize. However, the presence of the SCA effects suggested that dominance could be exploited to obtain desirable heterosis for grain yield (Amiruzzaman *et al*., 2013). Hallauer *et al*. (2010) showed that a little dominance can result is significant heterosis.

The interactions of the lines, tester hybrids and line x testers with the environment presents a challenge in breeding PVA maize hybrids. This showed that a large number of sites must be used during the selection of both the breeding materials as well as in the testing of the final hybrids that are produced from the promising lines. In line with this, Bernardo (2002) noted that increasing the number of replications per site, number of years or sites could greatly improve the genetic gains that could be observed in maize breeding. Low narrow sense heritability has been reported for a number of traits in maize that include grain yield. Thus, when traits are of low heritability, there is need to increase the number of replications in testing.

5.7 Conclusions

Additive gene action was predominant in the control of most traits studied, including grain yield. Narrow sense heritability was low for grain yield and other allied traits except SD and AD that had medium values. There was huge genetic variance attributed to lines, testers, and line x tester hybrids. Desirable inbred lines were identified as line 5 and 6 and tester 1 and 5, while the most desirable cross was 6 x 1. There were huge effects of the environment that would modify the genotypic effects across environments.

5.8 Recommendations

The presence of additive gene action for grain yield and other traits in a set of PVA maize inbred lines suggested that further genetic improvement of these traits is possible. However, given that the heritability ranged from moderate - low for many traits, hybrid testing must make use of replicated trials in many locations over seasons and/or years in order to increase on repeatability.

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Chapter 6 : AGRONOMIC PERFORMANCE

Abstract

Adoption of new varieties is highly dependent on their value as perceived by the farmers. In maize, grain yield is the most important trait that is highly considered by farmers. The agronomic performance of a set of pro-vitamin A (PVA) hybrids were compared to white and yellow maize counterparts. The objective of the study was to understand the yield gap between the PVA hybrids and either the white or the yellow maize. A total of 36 hybrids from different colours were evaluated at three locations namely Ukulinga, Cedara and Dundee during the 2014/15 summer season using a 6 x 6 α-lattice design with two replications. Analysis of variance showed that there were significant differences ($P<0.05$) on the genotype by environment interaction and hybrids. Although some PVA hybrids had comparable yield to white and yellow maize, the PVA hybrids yielded less than the white and yellow maize. The lower grain yield of PVA hybrids were associated with high root lodging (RL) and total lodging (TL). The three hybrids (14PVAH-22, 14PVAH-159 and 14PVAH-121) could be recommended for release as the only PVA hybrids in South Africa based on this study. The yield level of the PVA hybrids however should also be improved based on reducing the frequencies of lodging.

6.1 Introduction

Maize is the widely consumed and grown food crop in sub-Saharan Africa (Shiferaw et al., 2011). Producers of maize consider several agronomic traits in the choice of the varieties to grow (Vasal, 2000; Nyakurwa *et al*., 2017). Such factors include earliness, tolerance to pests and diseases, grain texture and plant appearance among others. However, grain yield remains the critical factor which farmers consider when selecting the type of varieties to grow irrespective of whether the crop is for food, feed or biofuel (Setimela *et al*., 2017a, b). Therefore, when new hybrids are developed, they should be able to compete with the existing checks in terms of grain yield and then be able to add additional value to the farmers or consumers (Pillay, 2011). The variety release committees in many countries consider this as value for use and cultivation.

In the past, there were efforts to develop high yielding hybrids in South Africa. To date, several hybrids are being grown commercially, including two, DKC80-40BRGEN and PAN6Q408CB, white maize varieties (Maphumulo *et al*., 2015). Following these hybrids, some yellow maize varieties were also produced. In South Africa, as in many African countries, people do not like yellow maize, rather they prefer white maize for human consumption (Pillay, 2011). However, the yellow hybrids are still being grown mainly for animal feed. In the recent past, research efforts extended to the development of orange maize hybrids in South Africa. Orange maize has several advantages of providing the most needed Vitamin A to human beings as well as their livestock (Stein, 2010). The adoption of orange maize as food or feed will depend on the ability to beat the existing yellow and white maize hybrids. This raises the need to evaluate the grain yield and related agronomic performance in orange maize compared to the existing yellow and white hybrid checks.

Achieving constant genetic gains is the major goal of most breeding programmes (Masuka *et al*., 2017a, b). This requires a thorough understanding of grain yield formation in maize (Gasura *et al*., 2014). Grain yield is a complex trait that is influenced by many physiological processes and associated secondary traits (Tollenaar and Lee, 2002). During crop breeding, some traits are optimized to ensure maximum resource capture and utilization in yield formation (Tollenaar and Lee, 2002). It is therefore essential in a maize breeding programme to understand traits that are associated with grain yield in diverse maize germplasm backgrounds. This allows breeders to understand traits that should be improved in order to achieve high grain yield. This concept of indirect selection is widely used in many crop plants especially when the secondary trait has high heritability are and highly correlated to the trait of economic importance such as grain yield (Gasura *et al*., 2013, 2014). The objective of this study was to understand whether orange maize hybrids can yield the same or better than the yellow and the white maize hybrids, and to identify traits that are associated with high grain yield in hybrids of different types.

6.2 Materials and methods

6.2.1 Plant materials

A total of 36 hybrids were used in the study. These hybrids were composed of experimental hybrids in the advanced stage of testing together with some five commercial check hybrids PAN4P228, BG5285, PAN6Q345CB, PAN6Q408CB, and DKC80-40BRGEN. The description of the materials is provided in Table 6.1.

6.2.2 Description of trial sites

Hybrids were evaluated at three sites Cedara, Dundee, and Ukulinga. The geographical descriptions of the sites are given in Table 6.2. The soil in the testing field of Ukulinga Research Farm is sandy clay-loam, fertile and friable with good water drainage (Cambisol). It is composed of 35% sand, 44% silt, 21% clay, 7.4 pH, 1.2% organic matter, 10.32 ppm available phosphorous (P), and cation exchange capacity (CEC) of 22.34 (meq/100 g). However, it is susceptible to cracking and crusting under flooding. Cedara research station falls entirely into the Moist Midlands Mistbelt (BRG 5). This BRG falls in the 900 – 1 400 m above sea level range and is generally hilly, rolling country with a high percentage of arable land, where 47% is suitable for cropping. Within this BRG, four Bioresource Units are found, three of which are most dominant. These are Xc15 (Cedara), Wc30 (Broadacres) and Yc14 (Byrne). Mean annual rainfall for this area ranges from 838 - 979 mm. Mean maximum January temperature for this farm is 25°C while mean minimum July temperature can drop as low as 4°C. Fertility is low, but physical properties are favourable. It is characterised by sandy clay soils which are reasonably fertile and well drained. Chances of flooding were very low due to a good slope and ground cover. Dundee falls into the Sour Sandveld Bioresource Group (BRG14). This BRG is recognized by the dominance of Hyparrhenia hirta grassland. Within this BRG, only one BRU is found. This is UVc6 (Dundee Proefplaas). Mean annual rainfall for this area is poor and erratic and approximately 743 mm. This falls mostly in the summer months. Mean maximum January temperature for this farm is 28°C while mean minimum July temperature can drop to as low as 2°C. Occasional severe frost can be experienced on the farm.

The fields at Ukulinga and Dundee were disc ploughed before planting although minimum tillage was done at Cedara. The Cedara field had high organic matter from the stover of preceding maize crop. The ground cover also provided mulch and helped in moisture conservation.

6.2.3 Experimental design and trial management

The 36 hybrids (Table 6.1) were evaluated on three sites (Table 6.2) in KwaZulu-Natal province of South Africa, during the 2014/15 summer cropping season. Two boarder rows were planted at the ends, around the experimental sites. All experiments were laid out as incomplete block designs consisting of 6 x 6 α-lattice design with two replications at all the sites. Each plot consisted of two rows of 5m length. Plants were spaced at 30 cm within rows and 90 cm between rows, giving a total of 32 plants per plot. A total of 250 kg/ha NPK (56N: 83P: 111K) compound fertilizer was applied as basal dressing during planting, immediately after planting curator was applied around the experimental site to repel rodents. The field was irrigated to establish the crop. Six weeks after planting, 250 kg/ha of lime ammonium nitrate (LAN 28% N) was applied as a top dressing. Weed control was achieved through both chemical such as Basagram (to kill nutsedge), Gramoxone (all fresh weeds) and Troopers (broadleaf weeds including morning glory) and hand weeding, and all sites were rainfed until hand harvesting after physiological maturity.

Table 6.1 Description of the pro-vitamin A, yellow and white hybrids used in the study

Entry code	Hybrid Name	Grain Colour
1	14PVAH-1	Orange
2	14PVAH-5	Orange
3	14PVAH-21	Orange
4	14PVAH-22	Orange
5	14PVAH-25	Orange
6	14PVAH-26	Orange
7	14PVAH-63	Orange
8	14PVAH-65	Orange
9	14PVAH-80	Orange
10	14PVAH-83	Orange
11	14PVAH-121	Orange
12	14PVAH-122	Orange
13	14PVAH-123	Orange
14	14PVAH-141	Orange
15	14PVAH-142	Orange
16	14PVAH-159	Orange
17	14PVAH-162	Orange
18	PAN4P228	White
19	DKC80-40BRGEN	White
20	11C1579	White
21	11C1774	White
22	11C1483	White
23	PAN6Q408CB	White
24	PAN6Q345CB	White
25	BG5285	White
26	10HDTX11	White
27	14C8430	Yellow
28	14C8431	Yellow
29	14C8433	Yellow
30	14C8434	Yellow
31	14C8435	Yellow
32	14C8436	Yellow
33	14C8438	Yellow
34	14C8439	Yellow
35	14C8441	Yellow
36	14C8442	Yellow

Table 6.2 Geographical coordinates and environmental conditions for the study sites

Sites	Latitude	Longitude	Altitude (metres above sea level)	Total season rainfall (mm)	Temperature range (ºC)
Cedara	29°.54'S	30°.26'E	1068	696.96	9.85 – 24.41
Dundee	28°.13'S	30°.31'E	1219	782.80	9.70 – 24.10
Ukulinga	29°.66'S	30°.40'E	809	676.17	13.65 – 24.83

6.3 Data collection

Data was collected following the standard protocols which are used at International Maize and Wheat Improvement Center (CIMMYT). Grain yield was measured as grain mass per plot adjusted to 12.5% grain moisture content at harvest. Ear prolificacy (EPP) was measured as the total number of ears per plot divided by the total number of plants per plot. Grain moisture content (MOI) was measured as percentage water content of grain measured at harvest. Plant height (PH) (cm) was measured as the distance from the base of plant to the insertion point of the top tassel. It was measured when all the plants had flowered, since plants reach their maximum height at flowering. Ear height (EH) (cm) was measured as height from ground level up to the base of the upper most ear. Ear position was measured as the ratio of ear height to plant height. Root lodging (RL) was measured as a percentage of plants that showed lodging by being inclined by up to 45°. Stem lodging (SL) was measured as a percentage of plants that were broken below the ear. TL was measured as the sum of RL and SL. Diseases that include gray leaf spot, Turcicum leaf blight, ear rots and Phaeosphaeria leaf spot were measured based on a 1-5 scale where 1 is a clean plant where 5 is a severely diseased plant.

6.4 Data analysis

Single site and combined analysis of variance (ANOVA) were done using Genstat software 17th edition (GenStat, 2014). Combined ANOVA was carried out using the following model:

$$Y_{ij(k)(l)} = b_j(r_k)(E_l) + r_k(E_l) + g_i + E_l + gE_{(il)} + e_{ij(k)(l)}$$

where $Y_{ij(k)(l)}$ is the response of the i^{th} genotype in the j^{th} incomplete block nested within the k^{th} replication nested in the l^{th} environment; $b_j r_{(k)} E_{(l)}$ is the effect of the j^{th} incomplete block nested in the k^{th} replication also nested in the l^{th} environment and j= 1, 2, 3…6; $r_k(E_l)$ is the effect of the k^{th} replication nested in the l^{th} environment and k= 1, 2; g_i is the effect of the i^{th} genotype and i= 1, 2, 3,...36; E_l is the effect of the l^{th} environment and l= 1, 2, 3; $gE_{(il)}$ is the interaction effect of the i^{th} genotype and the l^{th} environment; and $e_{ij(k)(l)}$ is the random error term.

The hybrids were grouped by colour, to form three groups of orange, yellow, and white. A two sample independent t-tests was used to do pairwise comparison of the group means found in each category.

6.5 Results

6.5.1 Analysis of variance, mean performance and group mean comparisons at Ukulinga

There were differences among the hybrids for GY, EPP, PH and ASI (P<0.001), PH and EPO (P<0.01) and MOI (P<0.05) (Table 6.3). However, there were insignificant differences among the hybrids for SL, RL and TL. Broad sense heritability was very low for all traits. Although some yellow hybrids such as 14C8434, 14C8433, and 14C8436 were ranking at the topmost, followed by the white hybrids such as PAN6Q345CB and BG5285, they were not statistically different from four orange hybrids (14PVAH-159, 14PVAH-121, 14PVAH-122, 14PVAH-120) based on the LSD of 1.54 t/ha (Table 6.4). However, a close look based on the differences in-group means reveal a separate pattern. The group of PVA hybrids had a lower mean grain yield compared to yellow, white and combined white and yellow (Table 6.5). Although the PVA hybrids had a higher EPP mean value than the yellow, their mean EPP value was not statistically different from the white hybrids. However, the PVA hybrids had statistically higher values for SL, RL and TL compared to either the yellow or the white hybrids.

6.5.2 Analysis of variance, mean performance and group mean comparisons at Cedara

There were highly significant differences among the hybrids for GY and EPP and significant (P<0.05) differences among hybrids for MOI, RL and TL. However, SL, GLS and PLS were insignificantly different (Table 6.6). Broad sense heritability was high for grain yield (71%) and other traits. A yellow hybrid was outstanding in GY performance (10.44t/ha), and this was followed by two PVA hybrids which were not statistically different from other commercial white and yellow maize hybrids (Table 6.7). A comparison of the hybrid group means showed the PVA hybrids had grain yield which was not statistically different from the yellow and white maize (Table 6.8). However, the EPP for PVA were not different from the white maize but statistically higher than the yellow. Furthermore, the PVA hybrids showed higher rates of RL and TL compared to either the white or the yellow maize hybrids.

6.5.3 Analysis of variance, mean performance and group mean comparisons at Dundee

At Dundee, significant differences ($P<0.05$) were found for PH, EH, EPO and EL. However, the rest of the traits did not show any differences among the hybrids (Table 6.9). Broad sense heritability was low (<50%) for all traits. A commercial white maize hybrid, PAN6Q408CB, was leading in terms of grain yield. This hybrid was followed by many yellow and some more white varieties. However, among the top hybrids, two PVA hybrids, 14PVAH-123 and 14PVAH-121, were found to be much closer in terms of grain yield. The mean yield of these two PVA hybrids were not significantly different from the other top hybrids except the top yielder, PAN6Q408CB (Table 6.10). When group comparisons were done, the results showed that the PVA hybrids yielded almost closer to 1.5 t/ha less than either the white or the yellow maize hybrids evaluated at this location (Table 6.11).

6.5.4 Analysis of variance, mean performance and group mean comparisons across sites

Genotype by environment interaction (GE) was present for GY, EPP, RL, and TL. The hybrids showed highly significant differences ($P<0.001$) for GY, EPP, MOI, RL and TL except SL which was significant at $P<0.05$ (Table 6.12). Broad sense heritability was high for grain yield (77%) and above 30% for the rest of the traits. The yellow hybrids ranked at the top, followed by two PVA hybrids and then some white maize hybrids (Table 6.13). However, the two PVA hybrids were not statistically different from the white and some yellow hybrids on the list (Table 6.13). Across sites, the PVA hybrids yielded 0.5 and 1.2 t/ha less than the white and yellow maize, respectively. However, the PVA hybrids had as high EPP as white maize but were much better than the yellow maize. However, the PVA hybrids had higher RL and SL values compared to either the white or the yellow maize hybrids.

Table 6.3 Mean square for hybrid traits at Ukulinga Research Farm

Source	DF	GY	EPP	PH	EH	EPO	MOI	ASI	SL	RL	TL
Rep	1	2.76*	0.03	722*	786.72**	0.004	4.16*	0.13	53.36*	2.53	32.64
Rep.Block	10	1.61**	0.11***	1086.1***	248.24**	0.002	1.20	0.50	17.32	108.45	114.77
NP	1	5.98**	0.29***	1267.8*	122.39	0.00009	3.37*	0.53	0.13	186.74	196.64
Entry	35	2.69***	0.16***	462.3**	422.42***	0.004**	1.66*	0.79***	10.25	88.3	129.29
Residual	24	0.51	0.02	167.50	73.81	0.001	0.65	0.23	12.46	51.15	51.57
Total	71	1.85	0.11	465.50	280.95	0.002	1.32	0.54	12.46	78.76	100.56
Mean		10.11	1.59	298.68	135.54	0.454	16.28	-0.93	1.90	4.66	6.56
σ^2G		2.44	0.16	378.55	385.52	0.003	1.34	0.67	4.02	62.73	103.51
σ^2E		2.69	0.16	462.30	422.42	0.004	1.66	0.79	10.25	88.30	129.29
σ^2P		15.24	1.91	1139.53	943.47	0.461	19.28	0.53	16.17	155.68	239.35
% GCV		15.43	24.83	6.51	14.49	12.067	7.10	-88.15	105.50	170.06	155.15
% ECV		16.22	25.49	7.20	15.16	13.105	7.92	-95.30	168.47	201.78	173.40
% H^2		0.16	0.08	0.33	0.41	0.007	0.07	1.27	0.25	0.40	0.43

DF-degrees of freedom, GY-grain yield, EPP-ears per plant, PH-plant height, EH-ear height, EPO-ear position, MOI-moisture content, ASI-anthesis-silking interval, SL-stem lodging, RL-root lodging, TL-total lodging, NP-number of plants, σ^2G-gentypic variance component, σ^2E-error variance component, σ^2P-phenotypic variance component, H^2 (%)-broad sense heritability, GCV-genetic coefficient of variation, ECV-error coefficient of variation. *-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 6.4 Hybrid means for various traits evaluated at Ukulinga Research Farm

Names	Entry	GY	EPP	PH	EH	EPO	MOI	ASI	SL	RL	TL
14C8434	30	12.04	1.31	328.90	157.70	0.48	17.91	-0.96	3.24	3.32	6.56
14C8433	29	11.66	1.37	332.20	150.20	0.45	16.95	-2.99	0.02	0.52	0.54
14C8436	32	11.66	1.29	295.60	154.80	0.52	17.31	-1.01	-0.02	-0.42	-0.43
PAN6Q345CB	24	11.17	1.96	301.60	128.30	0.43	14.21	-1.01	2.62	-0.42	2.20
BG5285	25	11.14	1.91	310.60	139.80	0.45	16.81	-1.01	-0.02	-0.42	-0.43
14PVAH-159	16	11.05	1.91	312.60	159.80	0.51	16.91	-1.01	2.62	15.81	18.43
10HDTX11	26	11.05	1.90	271.00	134.00	0.49	16.63	-0.02	-0.05	-1.35	-1.40
14C8441	35	11.03	1.02	281.60	118.80	0.42	17.01	-1.01	2.76	-0.42	2.35
14C8430	27	10.97	1.12	296.70	128.70	0.43	16.45	-0.99	2.96	0.52	3.48
14C8438	33	10.94	1.02	316.60	164.80	0.52	17.66	-1.01	-0.02	2.36	2.35
14PVAH-22	4	10.80	2.02	305.60	137.30	0.45	16.81	-0.51	2.76	15.37	18.14
DKC80-40BRGEN	19	10.78	1.76	299.90	131.10	0.44	15.19	-1.03	-0.08	-2.28	-2.36
14PVAH-123	13	10.60	1.99	283.90	127.60	0.45	17.24	-1.03	7.68	10.22	17.90
14C8435	31	10.51	1.48	314.00	150.50	0.48	16.13	-1.02	5.51	1.15	6.66
14PVAH-142	15	10.41	1.80	284.70	125.50	0.44	17.08	0.02	5.93	9.79	15.72
14C8431	28	10.33	1.11	306.00	122.50	0.40	15.63	-2.02	-0.05	-1.35	-1.40
14PVAH-21	3	10.31	2.00	301.20	145.00	0.48	16.48	-0.98	0.05	7.34	7.39
14PVAH-83	10	10.30	1.66	294.00	144.00	0.49	17.23	-1.02	-0.05	3.91	3.87
PAN6Q408CB	23	10.28	1.60	299.70	126.70	0.42	16.55	-0.99	0.02	0.52	0.54
14C8439	34	10.20	1.19	336.30	158.40	0.47	16.32	-1.97	0.09	2.39	2.47
LSD		1.54	0.28	27.85	18.49	0.07	1.74	1.03	7.60	15.39	15.46
CV		7.06	8.16	4.33	6.34	7.23	4.97	-51.19	185.77	153.58	109.52
Means		10.11	1.59	298.68	135.54	0.45	16.28	-0.93	1.90	4.66	6.56

GY-grain yield, EPP-ears per plant, PH-plant height, EH-ear height, EPO-ear position, MOI-moisture content, ASI-anthesis-silking interval, SL-stem lodging, RL-root lodging, TL-total lodging, LSD-least significant difference, CV-coefficient of variation.

Table 6.5 Hybrid groups comparisons at Ukulinga Research Farm

Group	Names	GY	EPP	PH	EH	EPO	MOI	ASI	SL	RL	TL
PVA	Mean	9.4594	1.7825	294.9941	134.7118	0.4576	16.3571	-0.7364	2.7101	9.3025	12.0127
	Variance	1.6984	0.0339	408.2393	176.7224	0.0015	0.6685	0.1637	5.9732	68.3774	92.7371
	N	17.0000	17.0000	17.0000	17.0000	17.0000	17.0000	17.0000	17.0000	17.0000	17.0000
PVA vs White	Mean	10.4222	1.6801	294.1222	130.3333	0.4439	15.6744	-0.7791	0.8733	-0.1037	0.7697
	Variance	0.3986	0.0549	202.4869	108.0625	0.0016	1.2609	0.6302	3.5305	1.3085	6.7752
	N	9.0000	9.0000	9.0000	9.0000	9.0000	9.0000	9.0000	9.0000	9.0000	9.0000
	difference	-0.9628	0.1024	0.8719	4.3784	0.0137	0.6826	0.0427	1.8367	9.4062	11.2430
	SED	0.3797	0.0899	6.8200	4.7331	0.0163	0.4236	0.2822	0.8623	2.0415	2.4916
	t-value	-2.5355	1.1387	0.1278	0.9251	0.8429	1.6115	0.1514	2.1299	4.6076	4.5124
	Tprob	0.0182	0.2661	0.8993	0.3641	0.4076	0.1201	0.8809	0.0436	0.0001	0.0001
PVA vs Yellow	Mean	10.9520	1.1932	309.0500	141.6200	0.4575	16.7030	-1.3969	1.4484	1.0444	2.4925
	Variance	0.4374	0.0256	394.4272	385.4884	0.0021	0.6305	0.4861	4.0314	2.3349	6.9396
	N	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000
	difference	-1.4926	0.5893	-14.0559	-6.9082	0.0002	-0.3459	0.6605	1.2617	8.2581	9.5202
	SED	0.3790	0.0675	7.9660	6.9960	0.0174	0.3200	0.2413	0.8686	2.0629	2.4797
	t-value	-3.9381	8.7337	-1.7645	-0.9875	0.0094	-1.0812	2.7372	1.4525	4.0031	3.8392
	Tprob	0.0006	0.0000	0.0899	0.3329	0.9926	0.2899	0.0112	0.1588	0.0005	0.0007

GY-grain yield, EPP-ears per plant, PH-plant height, EH-ear height, EPO-ear position, MOI-moisture content, ASI-anthesis-silking interval, SL-stem lodging, RL-root lodging, TL-total lodging, N-sample size, SED-standard eror of the difference

Table 6.6 Mean square for hybrid traits at Cedara Research Station

Source	DF	GY	EPP	MOI	SL	RL	TL	GLS1	PLS
Rep	1	1.21	0.01	2.76	130.8	993.6*	403.3	308.35***	210.13***
Rep.Block	10	2.53***	0.098**	1.11	804.9**	2392.2***	2164.8***	0.51	1.79*
NP	1	4.19**	0.77***	0.02	4	24	47.7	1.77	0.078
Entry	35	2.06***	0.12***	2.63**	364.2	687**	689.8**	0.63	0.65
Residual	24	0.36	0.02	0.89	211.10	233.50	214.70	0.89	0.66
Total	71	1.57	0.09	1.79	366.20	768.80	723.90	5.05	3.76
Mean		6.67	1.43	15.47	13.72	40.67	54.38	2.07	1.71
σ^2G		0.85	0.05	0.87	76.55	226.75	237.55	0.00	0.00
σ^2E		0.36	0.02	0.89	211.10	233.50	214.70	0.89	0.66
σ^2P		1.21	0.07	1.76	287.65	460.25	452.25	0.89	0.66
% GCV		13.84	15.24	6.03	63.79	37.03	28.34	0.00	0.00
% ECV		8.94	10.37	6.10	105.94	37.57	26.94	45.70	47.56
% H^2		0.71	0.68	0.49	0.27	0.49	0.53	0.00	0.00

DF-degrees of freedom, GY-grain yield, EPP-ears per plant, MOI-moisture content, SL-stem lodging, RL-root lodging, TL-total lodging, GLS-grey leaf spot, PLS-Phaesopharia leaf spot, NP-number of plants, σ^2G-gentypic variance component, σ^2E-error variance component, σ^2P-phenotypic variance component, H^2 (%)-broad sense heritability, GCV-genetic coefficient of variation, ECV-error coefficient of variation. *-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 6.7 Hybrid means at Cedara Research Station

Names	Entry	GY	EPP	MOI	SL	RL	TL	GLS1	PLS
14C8438	33	10.44	1.16	16.96	8.61	14.74	23.35	0.99	0.51
14PVAH-22	4	8.46	1.92	14.81	37.78	39.74	77.52	1.99	1.01
14PVAH-121	11	8.18	1.79	16.50	22.66	19.94	42.60	1.96	1.57
14C8439	34	7.92	1.22	16.57	5.44	54.47	59.91	2.01	0.98
14PVAH-159	16	7.83	1.84	16.62	46.04	27.10	73.14	1.51	0.98
14C8433	29	7.68	1.30	16.42	15.00	39.77	54.77	1.51	1.98
BG5285	25	7.54	1.42	13.46	6.16	40.99	47.14	1.49	2.01
14C8434	30	7.48	1.13	15.96	12.78	51.20	63.97	1.49	2.01
14C8441	35	7.28	1.14	18.05	37.21	23.81	61.02	1.46	1.07
14PVAH-1	1	7.21	1.76	15.56	4.12	64.55	68.67	1.97	1.04
PAN6Q345CB	24	7.11	1.79	14.81	1.18	79.09	80.27	1.47	2.04
PAN6Q408CB	23	7.10	1.71	15.10	13.84	23.19	37.03	1.46	2.57
14PVAH-123	13	7.06	1.50	16.65	10.59	36.96	47.55	1.46	2.07
14PVAH-122	12	6.99	1.64	16.57	32.83	48.41	81.24	1.51	1.98
14C8435	31	6.87	1.12	16.36	0.28	69.95	70.22	1.99	1.01
14PVAH-21	3	6.74	1.76	15.49	7.31	57.49	64.80	2.57	0.89
14PVAH-141	14	6.59	1.48	15.41	12.04	14.52	26.56	1.49	2.51
14PVAH-142	15	6.56	1.34	16.28	23.47	41.67	65.15	2.03	1.95
14C8436	32	6.53	1.13	16.36	39.16	39.39	78.56	2.99	1.01
14PVAH-83	10	6.45	1.09	15.87	13.82	73.76	87.58	2.51	1.48
Average		6.67	1.43	15.47	13.72	40.67	54.38	2.07	1.71
LSD		1.26	0.31	1.99	30.61	32.20	30.87	1.99	1.71
CV		8.94	10.37	6.10	105.94	37.58	26.94	45.70	47.56

GY-grain yield, EPP-ears per plant, MOI-moisture content, SL-stem lodging, RL-root lodging, TL-total lodging, GLS-grey leaf spot, PLS-Phaeospharia leaf spot, LSD-least significant difference, CV-coefficient of variation.

Table 6.8 Hybrid groups comparisons at Cedara Research Station

Group	Parameter	GY	EPP	MOI	SL	RL	TL	GLS	PLS
PVA (N=17)	Mean	6.5038	1.5572	15.5100	13.5712	51.5806	65.1518	2.2761	1.6011
	Variance	1.2425	0.0615	0.7538	197.3342	449.2431	330.3074	0.4631	0.2772
PVA vs White (N=9)	Mean	6.2870	1.4828	14.4000	8.7667	29.6089	38.3756	1.8719	2.1362
	Variance	0.5669	0.0644	0.9103	112.3446	641.4869	513.5244	0.1871	0.3643
	difference	0.2168	0.0745	1.1100	4.8045	21.9717	26.7762	0.4042	-0.5352
	SED	0.3689	0.1038	0.3814	4.9082	9.8845	8.7457	0.2192	0.2383
	t-value	0.5878	0.7175	2.9102	0.9789	2.2229	3.0616	1.8442	-2.2459
	Tprob	0.5622	0.4800	0.0077	0.3374	0.0359	0.0054	0.0775	0.0342
PVA vs Yellow (N=10)	Mean	7.3124	1.1568	16.3780	18.4130	32.0700	50.4830	1.8961	1.5061
	Variance	1.5792	0.0042	0.7628	302.6396	492.7982	513.8574	0.3274	0.5435
	difference	-0.8086	0.4004	-0.8680	-4.8418	19.5106	14.6688	0.3800	0.0950
	SED	0.4806	0.0635	0.3473	6.4708	8.7009	8.4152	0.2449	0.2658
	t-value	-1.6823	6.3064	-2.4993	-0.7483	2.2424	1.7431	1.5514	0.3572
	Tprob	0.1050	0.0000	0.0194	0.4613	0.0340	0.0936	0.1334	0.7239

GY-grain yield, ASI, anthesis-silking interval, EH-ear height, EL-ear length, EPO-ear position, MOI-moisture content, PH-plant height, RL-root lodging, SL-stem lodging, TL-total lodging, N-sample size, SED-standard error of the difference.

Table 6.9 Mean square for hybrid traits at Dundee Research Station

Source	DF	GY	ASI	EH	EL	EPO	EPP	MOI	PH	RL	SL	TL
Rep	1	1.69	0.35	68.1	0.39	0.00004	0.015	9.54	490.9	620.6	2289.1*	5293.6*
Rep.Block	21	9.86***	1.35	447.3**	5.78**	0.003	0.31***	3.58	927.6***	785.7**	1219.8**	3291.5**
NP	1	4.17	0.02	1348.3**	6.50*	0.011*	0.59**	0.43	960.1*	14.5	27.8	82.5
Entry	34	1.33	1.17	332.8**	5.87***	0.004*	0.089	2.56	349.9*	338.5	600.1	1639
Residual	14	1.08	1.24	120.40	1.26	0.002	0.06	3.69	152.60	233.60	316.70	882.80
Total	71	2.49	1.19	287.70	4.23	0.003	0.12	3.15	375.20	365.40	607.30	1645.70
Mean		3.08	0.18	106.28	18.25	0.429	1.16	11.30	247.70	20.52	41.72	62.24
σ^2G		0.12		106.20	2.30	0.001	0.01		98.65	52.45	141.70	378.10
σ^2E		1.08	1.24	120.40	1.26	0.002	0.06	3.69	152.60	233.60	316.70	882.80
σ^2P		1.21	1.21	226.60	3.57	0.003	0.08	3.13	251.25	286.05	458.40	1260.90
% GCV		11.44		9.70	8.32	7.961	9.64		4.01	35.29	28.53	31.24
% ECV		33.79	617.75	10.32	6.15	10.354	21.74	17.00	4.99	74.47	42.66	47.74
% H^2		0.10	-0.03	0.47	0.65	0.372	0.16		0.39	0.18	0.31	0.30

DF-degrees of freedom, GY-grain yield, ASI, anthesis-silking interval, EH-ear height, EL-ear length, EPO-ear position, MOI-moisture content, PH-plant height, RL-root lodging, SL-stem lodging, TL-total lodging, NP-number of plants, σ^2G-gentypic variance component, σ^2E-error variance component, σ^2P-phenotypic variance component, H^2 (%)-broad sense heritability, GCV-genetic coefficient of variation, ECV-error coefficient of variation. *-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 6.10 Hybrid means at Dundee Research Station

Names	Entry	GY	ASI	EH	EL	EPO	EPP	MOI	PH	RL	SL	TL
PAN6Q408CB	23	5.91	-1.14	95.70	19.29	0.42	1.34	11.21	232.40	13.41	12.04	25.45
14C8438	33	5.18	-0.02	123.70	18.95	0.47	1.22	12.60	262.80	65.20	91.97	157.17
14C8430	27	4.84	-0.18	115.10	17.94	0.44	1.53	10.71	263.60	19.78	69.77	89.55
PAN4P228	18	4.83	0.64	95.30	19.45	0.38	1.66	11.04	251.00	29.86	44.76	74.62
DKC80-40BRGEN	19	4.76	-0.14	113.20	18.29	0.47	1.61	11.16	242.40	12.09	24.36	36.45
10HDTX11	26	4.39	0.55	108.40	18.40	0.45	1.43	11.99	244.00	7.17	19.15	26.32
PAN6Q345CB	24	4.35	0.11	108.70	20.85	0.41	1.66	10.49	261.20	37.85	92.24	130.09
14C8442	36	4.30	0.55	95.40	21.40	0.39	1.26	10.19	242.50	8.19	47.36	55.55
14PVAH-123	13	3.83	0.05	102.40	20.90	0.41	1.39	12.49	249.00	21.02	54.54	75.55
14C8435	31	3.62	-0.02	119.70	19.70	0.49	0.95	11.80	245.30	7.51	26.58	34.10
14C8436	32	3.61	1.05	128.40	18.15	0.50	1.06	13.64	255.50	18.36	58.09	76.45
14C8431	28	3.45	0.08	76.60	19.75	0.32	1.30	11.79	241.30	7.09	24.91	32.00
14C8441	35	3.42	0.58	94.10	18.75	0.40	1.08	12.39	235.80	55.61	63.02	118.63
11C1483	22	3.14	0.05	97.90	16.10	0.38	1.28	11.84	257.00	7.17	14.28	21.45
14PVAH-121	11	3.08	0.05	116.90	17.90	0.43	1.12	13.24	270.00	27.59	40.53	68.12
14PVAH-141	14	2.97	0.58	107.60	20.75	0.42	1.26	9.99	256.30	23.44	51.35	74.79
14C8434	30	2.96	0.64	121.80	17.45	0.47	1.24	12.64	261.00	20.49	47.67	68.16
14PVAH-65	8	2.82	-0.14	95.20	16.79	0.43	1.33	9.36	220.40	17.26	40.25	57.50
14PVAH-83	10	2.79	0.14	106.30	19.70	0.40	1.01	12.04	261.50	7.99	28.71	36.70
14C8433	29	2.69	-0.42	137.10	18.75	0.53	0.87	13.09	258.80	20.84	35.16	56.01
Mean		3.08	0.18	106.28	18.25	0.43	1.16	11.30	247.70	20.52	41.72	62.24
LSD		2.22	2.38	23.38	2.39	0.09	0.54	4.09	26.31	32.56	37.91	63.30
CV		33.79	617.68	10.32	6.15	10.36	21.74	17.00	4.99	74.47	42.66	47.74

GY-grain yield, ASI, anthesis-silking interval, EH-ear height, EL-ear length, EPO-ear position, MOI-moisture content, PH-plant height, RL-root lodging, SL-stem lodging, TL-total lodging, LSD-least significant difference, CV-coefficient of variation

Table 6.11 Comparison of pro-vitamin A vs Yellow, white and combined yellow and white hybrids evaluated at Dundee Research Station

Group	Parameter	GY	ASI	EH	EL	EPO	EPP	MOI	PH	RL	SL	TL
PVA (N=17)	Mean	2.3528	0.2109	105.2882	17.7312	0.4277	1.0782	10.8718	245.9588	19.3765	37.7271	57.1029
	Variance	0.4833	1.2294	137.0536	6.9119	0.0011	0.0703	3.1029	448.5576	178.0762	174.5191	619.6401
White (N=9)	Mean	3.8078	0.1711	99.0556	18.5356	0.4019	1.3424	11.1800	247.0778	20.1833	41.9122	62.0956
	Variance	1.8585	0.3998	103.6253	2.4249	0.0018	0.0727	0.2320	194.7869	124.0367	832.1320	1486.4689
	difference	-1.4550	0.0398	6.2327	-0.8044	0.0258	-0.2642	-0.3082	-1.1190	-0.8069	-4.1852	-4.9926
	SED	0.4847	0.3417	4.4245	0.8222	0.0161	0.1105	0.4564	6.9303	4.9251	10.1353	14.1990
	t-value	-3.0019	0.1165	1.4087	-0.9783	1.6057	-2.3911	-0.6754	-0.1615	-0.1638	-0.4129	-0.3516
	Tprob	0.0062	0.9082	0.1718	0.3377	0.1214	0.0250	0.5059	0.8731	0.8712	0.6833	0.7282
Yellow (N=10)	Mean	3.6547	0.1374	114.4600	18.8890	0.4544	1.1442	12.1340	251.2300	22.7830	48.3280	71.1130
	Variance	0.7824	0.3290	379.7671	1.3298	0.0048	0.0406	1.0982	104.0579	436.8608	527.3931	1741.8824
	difference	-1.3019	0.0735	-9.1718	-1.1578	-0.0266	-0.0660	-1.2622	-5.2712	-3.4065	-10.6009	-14.0101
	SED	0.3266	0.3244	6.7852	0.7345	0.0233	0.0905	0.5407	6.0656	7.3594	7.9376	14.5134
	t-value	-3.9864	0.2265	-1.3517	-1.5762	-1.1406	-0.7287	-2.3345	-0.8690	-0.4629	-1.3355	-0.9653
	Tprob	0.0005	0.8226	0.1886	0.1275	0.2648	0.4730	0.0279	0.3931	0.6475	0.1937	0.3436

GY-grain yield, ASI, anthesis-silking interval, EH-ear height, EL-ear length, EPO-ear position, MOI-moisture content, PH-plant height, RL-root lodging, SL-stem lodging, TL-total lodging, N-sample size, SED-standard error of the difference.

Table 6.12 Mean square for hybrid traits across three sites

Change	d.f.	GY	EPP	MOI	SL	RL	TL
Site	1	425.99***	0.99***	23.52***	5024.6***	46685.1***	82341.5***
Site.Rep	2	1.98*	0.02	3.46*	92.1	498*	218
Site.Rep.Block	20	2.07***	0.10***	1.15	411.1***	1250.3***	1139.8***
NP	1	9.90***	1.03***	1.20	1.7	27.2	15.4
Entry	35	3.77***	0.25***	3.24***	201*	387.3***	484.9***
Site.Entry	35	0.99**	0.03*	1.09	172.3	393.1***	338.5**
Residual	49	0.43	0.02	0.77	110.4	139.60	132.00
Total	143	4.68	0.10	1.71	223.1	747.30	985.20
Mean		8.39	1.51	15.88	7.81	22.66	30.47
σ^2G		0.84	0.06	0.62	22.65	61.93	88.23
σ^2GE		0.28	0.01	0.16	30.95	126.75	103.25
σ^2E		0.43	0.02	0.77	110.40	139.60	132.00
σ^2P		9.94	1.59	17.43	171.81	350.94	353.95
% ECV		7.77	9.13	5.54	134.58	52.14	37.71
% GCV		10.89	15.89	4.94	60.96	34.73	30.83
% H^2		0.77	0.87	0.69	0.34	0.39	0.51

Degrees of freedom, GY-grain yield, EPP-ears per plant, MOI-moisture content, SL-stem lodging, RL-root lodging, TL-total lodging, σ^2G-genotypic variance component, σ^2GE-genotype x environment variance component, σ^2E-error variance component, σ^2P-phenotypic variance component, ECV-error coefficient of variation, GCV-genotypic coefficient of variation, H^2 (%)-broad sense heritability, *-significant at 5% probability level, ** -significant at 1% probability level, ***-significant at 0.1% probability level.

Table 6.13 Hybrid means across three sites

Name	Entry	GY	EPP	MOI	SL	RL	TL
14C8438	33	10.69	1.09	17.32	4.37	8.58	12.95
14C8434	30	9.81	1.22	16.78	6.93	26.89	33.82
14C8433	29	9.68	1.33	16.68	7.47	20.13	27.60
14PVAH-22	4	9.63	1.97	15.82	20.34	27.58	47.93
14PVAH-159	16	9.43	1.87	16.80	24.58	21.54	46.12
BG5285	25	9.34	1.67	15.15	3.15	20.31	23.46
14C8441	35	9.16	1.08	17.49	19.71	11.60	31.31
14PVAH-121	11	9.16	1.90	16.81	15.07	27.63	42.69
PAN6Q345CB	24	9.15	1.88	14.49	1.79	39.30	41.10
14C8436	32	9.09	1.21	16.85	19.65	19.51	39.16
14C8439	34	9.09	1.20	16.36	2.15	28.22	30.37
14PVAH-123	13	8.82	1.75	16.99	9.43	23.69	33.12
PAN6Q408CB	23	8.72	1.66	15.74	6.36	11.66	18.02
14C8430	27	8.69	1.15	15.88	26.77	3.40	30.18
14C8435	31	8.67	1.30	16.29	3.25	35.67	38.93
14PVAH-21	3	8.52	1.88	16.02	3.89	32.48	36.37
14PVAH-142	15	8.49	1.57	16.66	14.56	25.68	40.24
14PVAH-122	12	8.45	1.70	16.30	17.70	30.18	47.88
10HDTX11	26	8.35	1.78	15.47	0.75	20.06	20.81
14PVAH-83	10	8.35	1.38	16.62	7.43	39.02	46.45
Mean		8.39	1.51	15.88	7.81	22.66	30.47
LSD		0.94	0.20	1.28	15.21	17.11	16.64
CV		7.77	9.13	5.54	134.58	52.13	37.71

GY-grain yield, EPP-ears per plant, MOI-moisture content, SL-stem lodging, RL-root lodging, TL-total lodging, LSD-least significant difference, CV-coeffeicnt of variation.

Table 6.14 Hybrid groups comparisons across three sites

Group	Parameter	GY	EPP	MOI	SL	RL	TL
PVA (N=17)	Mean	7.9757	1.6697	15.9500	8.2692	30.4841	38.7547
	Variance	1.2852	0.0410	0.5745	54.7325	75.3938	80.2206
Combined White and Yellow	Mean	8.7687	1.3676	15.8111	7.3944	15.6621	23.0579
	Variance	0.6088	0.0680	1.1409	56.4248	134.5378	134.9605
	N	19.0000	19.0000	19.0000	19.0000	19.0000	19.0000
	difference	-0.7930	0.3021	0.1389	0.8748	14.8220	15.6968
	SED	0.3281	0.0774	0.3063	2.4878	3.3935	3.4383
	t-value	-2.4171	3.9021	0.4536	0.3516	4.3678	4.5653
	Tprob	0.0212	0.0004	0.6530	0.7273	0.0001	0.0001
White (N=9)	Mean	8.3597	1.5817	15.0189	4.6987	14.7100	19.4111
	Variance	0.3674	0.0451	0.7467	23.5728	156.0122	120.2445
	difference	-0.3840	0.0880	0.9311	3.5706	15.7741	19.3436
	SED	0.3412	0.0861	0.3417	2.4164	4.6658	4.2520
	t-value	-1.1253	1.0220	2.7249	1.4777	3.3808	4.5493
	Tprob	0.2716	0.3170	0.0118	0.1525	0.0025	0.0001
Yellow (N=10)	Mean	9.1369	1.1750	16.5240	9.8206	16.5190	26.3400
	Variance	0.5730	0.0089	0.4258	78.0885	128.6757	137.7688
	Difference	-1.1612	0.4947	-0.5740	-1.5514	13.9651	12.4147
	SED	0.3646	0.0575	0.2764	3.3209	4.1596	4.3007
	t-value	-3.1852	8.6067	-2.0770	-0.4672	3.3573	2.8867
	Tprob	0.0039	0.0000	0.0482	0.6444	0.0025	0.0079

GY-grain yield, EPP-ears per plant, MOI-moisture content, SL-stem lodging, RL-root lodging, TL-total lodging, n-sample size, SED-standard error of the difference.

6.6 Discussion

The PVA hybrids are new in South Africa, but they are proving to be yielding less than the known commercial check hybrids. However, in this study, some promising PVA hybrids such as 14PVAH-22, 14PVAH-159 and 14PVAH-121 were found to have yield at par with some yellow and white maize hybrids. Given their nutritional benefits, these hybrids could be augmented with some awareness campaigns when they are released on the market. However, farmers would be much more interested in the grain yield than the nutritional benefits which they cannot easily quantity (Nyakurwa *et al*., 2017). Therefore, government policies that encourage paying a premium price to the producers of orange maize would also attract farmers to produce these hybrids.

In this study, the PVA hybrids proved to be yielding about 0.5 t/ha and 1.2 t/ha less than the white and the yellow maize, respectively. More breeding activities are therefore required to improve the grain yield of PVA hybrids in South Africa. This study highlighted some areas in which the genetic improvements are required. The PVA hybrids have been greatly improved for the EPP, which were at par with white maize but higher than the yellow maize. Increasing the prolificacy of maize plants has been perceived as one approach of increasing grain yield (Banziger *et al*., 2006). However, for the benefit of future genetic improvements, it is essential to understand some areas that are still lacking in PVA maize genetic improvement. The lower yield in PVA was also accompanied by much higher levels of root and total lodging in almost all sites and across sites. This suggested that these traits must be improved.

Maize genetic gains have been improved through breeding for increased stress tolerance in the newer hybrids compared to the older hybrids (Masuka *et al*., 2017a,b). it was Recently demonstrated that increased genetic gains in maize could be improved by increasing density stress tolerance. Increasing the number of plants per unit area will directly improve grain yield per unit land. However, when the plant density is increased, plants will compete for resources that include sunlight, soil moisture and space. This normally results is relatively etiolated, slender and weaker plants resulting in increased stem lodging. Root lodging would also be high especially given that the plants would have been bred for high EPP and grain yield, hence the stems sometimes fail to support the cob resulting in root lodging.

Root, stem and total lodging have many ways of decreasing grain yield. The first would be the reduced photosynthesis rate due to mutual shading, furthermore, the uptake of water and nutrients would be compromised. Furthermore, during combine harvesting, the fallen plants are normally not harvested thus translating to less yield. In a breeding programme, it is therefore essential to ensure that the PVA hybrids are improved concerning tolerance to lodging stress. This would involve selecting PVA inbred lines that are resistant to lodging. A tester susceptible to lodging will be required in assessing the testcross performance of some promising inbred lines in different breeding programmes.

6.7 Conclusions

The following conclusions were drawn:

- Promising PVA hybrids such as 14PVAH-22, 14PVAH-159 and 14PVAH-121 have been found to have yield at par with some yellow and white maize hybrids.
- PVA hybrids are yielding about 0.5t/ha and 1.2 t/ha less than the white and the yellow maize, respectively.
- Low yield in PVA hybrids was associated with increased levels of root and total lodging.

6.8 Recommendations

The success of new maize hybrids depends on several factors that include grain yield potential in comparison to the common checks (Maphumulo *et al*., 2015).

- The promising PVA hybrids such as 14PVAH-22, 14PVAH-159 and 14PVAH-121 were found to yield at par with some yellow and white maize hybrids and must be taken for further testing for consideration of release.
- Root lodging and total lodging must be reduced in PVA maize hybrids in addition to some other traits with negative effects on grain yield.

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Chapter 7 : WRAPPING UP THE COMPLETED RESEARCH

General discussion, conclusions and recommendations

7.1 General discussion

In sub-Saharan Africa (SSA), maize is a leading staple crop (Shiferaw *et al*., 2011). The rapid growing population in the region would require adequate amounts of maize with high nutritional value. Malnutrition has been rampant in the region because the majority of people use diets that are mainly based on cereal grains, with limited income to diversify their foods (Vasal, 2000). Cereal grains are deficient in a number of nutrients, including vitamin A. Crop bio-fortification seems to be a more affordable and sustainable strategy for addressing malnutrition in SSA compared to other strategies such as use of micronutrient supplements and commercial fortification of foods, most of which have been tried with unsatisfactory nutrition outcomes. Biofortification is technically sound, especially when applied on the major staple crops such as cereal grains, especially maize grain in SSA.

In the past, bio-fortification of maize was focused on the improvement of protein quality (Vasal, 2000). A maize mutant with elevated levels of amino acids, lysine and tryptophan, was developed (Vivek, 2008). Recently, efforts were focused on the development of orange maize that is rich in the pro-Vitamin A (PVA), a precursor of the Vitamin A in the carotenoids biosynthesis pathway. Thus, improved maize grain quality would help to curb some major malnutrition challenges that are faced by most people in developing countries, and these include night blindness, reduced immunity, reduced growth and productivity (Nyakurwa *et al*., 2017).

In this study, the potential of developing PVA maize hybrids that are preferred by farmers was demonstrated. A study to assess the acceptance of fresh PVA orange maize grain in KwaZulu-Natal province showed that the PVA maize was preferred compared to white maize. Furthermore, the youth showed higher preference for PVA maize than adults did. This study showed the potential of PVA orange maize for adoption in South Africa. Furthermore, the youth will be the centre of the economic and decision making management in the future, thus their strong affiliation to PVA is a huge advantage for increasing adoption in the future. Normally, when new products are introduced on the market, consumers do not readily take them due to changes in the sensory characteristics. However, given the advantages of PVA maize, there is need to raise awareness campaigns on their health benefits. Furthermore, government policies that support the payment of higher prices for PVA maize hybrids would encourage production of this type of maize (Nyakurwa *et al*., 2017). If PVA maize is produced in excess, it can also be fed to livestock, and thus the vitamins would be obtained indirectly from animal products rather than the maize, which some people may not prefer.

New crop varieties should be highly adapted to their production environments (Yan and Tinker, 2006; Gauch, 2013). In this study, the genotype by environment interaction (GE) of the new PVA hybrids were assessed. The GE was present on the tested hybrids. The PVA hybrids were found to be most stable and high yielding and were comparable to the common check hybrids grown in South Africa. The identification of highly stable and high yielding PVA hybrids suggested that these materials can be grown by farmers in different production areas in the country. This would come as a big advantage in spreading PVA maize in different regions in order to reach the majority of farmers who are in need on this technology.

Understanding combining ability and gene action is critical in designing a viable breeding programme (Pswarayi and Vivek, 2008). The concept of combining ability was widely used in the choice of parents based on their general combining ability (GCA) and the choice of hybrids based on their specific combining ability (SCA) (Sprague and Tatum, 1942; Griffing, 1956). The relative magnitude of additive and non-additive genetic variance are essential in choosing breeding and testing methods (Hallauer *et al*., 2010). In this study, the GCA and SCA effects in the PVA germplasm were investigated. Both GCA and SCA effects were important in governing grain yield and other allied traits. However, the presence of SCA variance suggested the hope to develop hybrids that show higher heterosis. In general, SCA is positively correlated to heterosis and it also indicates that the germplasm used in the crosses would be genetically diverse (Amiruzzaman *et al*., 2013). In this study, heterosis was expected since the PVA hybrids were not only crossed to other PVA inbred lines but also to quality protein and normal maize. Furthermore, the lower ratio of additive genetic variance, coupled to relatively low narrow sense heritability for grain yield and allied traits suggested that a hybrid breeding programme is required. The interaction of non-additive gene action and environment was present. This suggested that the developed hybrids must be tested in many locations and many replications in order to identify the stable and high yielding hybrids. Based on their GCA values, inbred lines 4, 10 and 5 were found to be the best for improving grain yield and related traits. However, the best hybrids were 14PVAH 22, 14PVAH 159 and 14PVAH 121 based on the high positive SCA values for grain yield and high *per se* performance in grain yield.

Grain yield performance is the major driver of adoption of a new variety by farmers (Setimela *et al*., 2017a, b). Thus, when new varieties are developed, they must be compared with the existing check hybrids in order to have a glimpse of their potential adaptability. In this study, the high yielding and stable PVA hybrids were tested against the yellow and white check hybrids. Some of these check hybrids are already released in the country while some other check hybrids were previously developed from the maize breeding programme at the University of KwaZulu Natal. In this comparative study, three PVA hybrids proved to be having high yield comparable to the white and yellow maize at single and across site basis. However, when the groups of the PVA hybrids were compared to the group of either yellow or white hybrids, a fascinating trend was observed. The grain yield of the PVA hybrids was 0.5t.ha and 1.2t/ha less that the white and yellow maize, respectively. Accompanied to this low yield in PVA hybrids was RL and TL. Thus, in future breeding programmes, lodging must be improved. This involves using a lodging susceptible tester in the breeding programme in order to identify inbred lines with higher contribution to lodging stress tolerance. Another approach would be to include inbred lines with general resistance to lodging such as from the Iowa Stiff-Stalk Synthetic population. Breeding for stress tolerance has been the general trend used by plant breeders to increase the yield genetic gains in many crops including maize. In the current practises, maize density must be increased per unit area, in order to increase production per unit of land. This would therefore entail selecting maize hybrids with increased tolerance to lodging especially under high population density.

7.2 General conclusions

- In South Africa, fresh PVA maize hybrids were preferred to white maize. Furthermore, more youths liked fresh PVA maize compared to the adults.
- Genotype by environment interaction was present among the tested hybrids and the most stable and high yielding hybrids were 14PVAH 22, 14PVAH 159 and 14PVAH 121.
- Based on their GCA values, inbred lines 1, 5 and 6 and testers 5, 6 and 7 were found to be the best for improving grain yield and related traits. However, the best hybrids were

14PVAH 22, 14PVAH 159 and 14PVAH 121 based on the high positive SCA values for grain yield and high *per se* performance.

- Some PVA hybrids had comparable yield to white and yellow maize, however, the PVA hybrids generally showed less yield than the white and yellow maize. The lower grain yield of PVA hybrids were associated with high RL and TL.

7.3 General recommendations

Awareness campaigns should be provided to farmers and in particular to the youth who showed strong preference for PVA hybrids. The high yielding and table hybrids are highly recommended for release 14PVAH-22, 14PVAH-159, and 14PVAH-121). The desirable inbred lines could be used in further improvement of grain yield in PVA maize namely 1, 5 and 6 and tester 5,6 and 7. In future, the grain yield of PVA hybrids must be improved, with specific emphasis focused on improving lodging resistance. Policy to reward bio-fortified maize could be used to increase its production by farmers

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