BREEDING RICE FOR GRAIN YIELD, EARLINESS AND GRAIN QUALITY IN EASTERN AFRICA

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DECLARATION

I, Yuga Mario Enock, do hereby declare that this thesis is my original work and has not been submitted for any degree or examination at any other University. This thesis has a similarity index of 14 %. It does not contain other person's data, graphs, pictures or other information unless specifically acknowledged as being sourced from other persons.

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DEDICATION

To God my savior through whom all things are possible.

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LIST OF ACRONYMS AND SYMBOLS

2-AP	2-Acetyl-1-pyrolline
AATF	African Agricultural Technology Foundation
AGD-R	Analysis of Genetic Designs
AGRA	Alliance for a Green Revolution in Africa
ANOVA	Analysis of variance
ARI	Tanzania Agricultural Research Institute
ASV	Alkali Spreading Value
BC_2 F_1	Second backcross generation
cm	centimeter
CMS	Cytoplasmic Male Sterility
CV	Coefficient of variation
DNA	Deoxyribonucleic acid
F_1	First generation
FAO	Food and Agricultural Organization
FAOSTAT	Food and Agricultural Organization Statistics
g/L	grams per liter
GCA	General combining ability
ICRC	Industrial Crop Research Center
IRRI	International Rice Research Institute
JIRCAS	Japan International Research Centre for Agricultural Sciences
KAFACI	Korea Africa Food and Agriculture Cooperation Initiative
KALRO	Kenya Agriculture and Livestock Research Organization
KARI	Kenya Agricultural Research Institute
KATRIN	Kilombero Agricultural Research and Training Institute
KEPHIS	Kenya Plant Health Inspectorate Service
$Kgha^{-1}$	Kilograms per hectare
KOH	Potassium hydroxide
kPa	Kilopascal
L/W	Length to width ratio
LSD	Least Significant Differences
ml/L	Milliliter per liter
mm	Millimeter
MOA	Ministry of Agriculture
NERICA	New Rice for Africa
NIB	National Irrigation Board
OECD	Organization for Economic Cooperation and Development
Ppb	Parts-per-billion
QTL	Quantitative trait loci
RDA	Rural Development Administration
SCA	Specific combining ability
SES	Standard Evaluation System
UK	United Kingdom
UN	United Nations
WARDA	West African Rice Development Association
WFP	World Food Program

ABSTRACT

Rice is one of the most important cereal crops in Eastern Africa and it's often ranked after sorghum, wheat and maize. Unfortunately, rice yield per hectare is low (<3.6 t ha^{-1}) because smallholder farmers rely on local rice cultivars with low yield potential, poor grain quality, highly susceptible to bacterial leaf blight and rice blast. The deficit of about 75 % is imported from Pakistan, Vietnam and China. Therefore, development of high yielding and locally adapted rice varieties combining high grain quality with other farmer, processor and consumer preferred traits is probably the most effective strategy of increasing rice production in Eastern Africa. The main objective of this study was to contribute to increased rice productivity through the development of improved, locally adapted rice varieties with high yield potential, earliness and high grain quality. The specific objectives were i) to determine the combining ability and heterosis for agronomic and yield traits in indica and japonica rice crosses, and ii) to select for yield potential, earliness and grain quality from existing $F_{2.3}$ families. For the combining ability trial, 27 F_1 progenies were generated from crosses between nine male indica parents and three japonica female using North Carolina Design II mating system. In the second trial, 16 F_2 segregating populations and six commercial checks were evaluated in the short rain season between September and December 2016 at Mwea Research Station and Kirogo Experimental Farm in a randomized complete block design with three replications. Seven outstanding F_3 families were selected from the segregating populations and advanced for further evaluation during the long rain season between April and September 2017 at two sites. Data was collected on agronomic and yield traits. The physico-chemical characteristics of the $F_{2.3}$ families were analyzed in the Food Science Laboratory at University of Nairobi.

The results showed that general combining ability (GCA) variances were higher than specific combining ability (SCA) variances implying the predominant role of additive gene action in the expression of days to 50 % flowering, days to maturity, number of tillers $plant^{-1}$, number of spikelet's $panicle^{-1}$, number of panicles $plant^{-1}$, number of filled grains $panicle^{-1}$, and grain yield. Specific combining ability was significant ($P \leq 0.05$) for plant height, panicle length, flag leaf length and 1000-seed mass. Heterosis for grain yield was observed in the hybrids K_{2}-9 x Basmati 370 (31 %), K_{2}-9 x Komboka (24 %), K_{2}-8 x Basmati 217 (23 %), K_{2}-54 x Basmati 217 (21 %), K_{2}-54 x *Dourado precoce* (20 %) and K_{2}-8 x Basmati 370 (18 %). Heterosis for number of tillers $plant^{-1}$, panicle length, number of panicles $plant^{-1}$ and filled grains panicle^{-1} was observed in the F_1 hybrids. Negative heterosis for earliness was observed in the hybrids K_2-54 x Basmati 370 (-8 %) and K_2-54 x *Dourado precoce* (-4 %).

Evaluation of the $F_{2.3}$ families for agronomic and yield traits showed that the $F_{2.4}$ families of WAB-56-104 x NERICA 4, NERICA 4 x MWUR 4, NERICA 4 x NERICA 1 and NERICA 10 x KUCHUM were early maturing and consistently maintained higher grain yields in all locations indicating a wider adaptability to varying environments. The grain quality analysis showed that $F_{2.4}$ families of NERICA 4 x MWUR 4, NERICA 4 x NERICA 1 and NERICA 10 x KUCHUM exhibited slender grain shape while NERICA 4 x NERICA 1 (22.33 minutes) followed by WAB-56-104 x NERICA 4 (22.67 minutes) and MWUR 4 x NERICA 4 (23.33 minutes) cooked fast with soft cooked texture and recorded low gelatinization temperatures. The $F_{2.4}$ families of WAB-56-104 x NERICA 4, NERICA 4 x MWUR 4, MWUR 4 x NERICA 4 and CG 14 x NERICA 10 had mild aroma while NERICA 4 x NERICA 1, NERICA 13 x K45 and NERICA 10 x KUCHUM were non-aromatic.

Out of the 12 parents evaluated for general combining ability, only four parents namely Basmati 370, Basmati 217, K_2-54 and Komboka were good general combiners for grain yield. From 27 F_1 hybrids evaluated for specific combining ability, four F_1 hybrids namely K_2-9 x Komboka, K_2-9 x Basmati 370, K_2-54 x *Dourado Precoce* and K_2-54 x Basmati 217 were good specific combiners and expressed better heterotic effects for grain yield. The check Basmati 370 was outstanding for physical grain quality and aroma compared to the non-Basmati rice genotypes suggesting that Basmati 370 has implication for future breeding. From the 16 populations evaluated, three families namely MWUR 4 x NERICA 4, NERICA 4 x NERICA 1 and WAB-56-104 x NERICA 4 exhibited better agronomic, culinary and physico-chemical qualities. However, there is need to advance these $F_{2.4}$ families for further selection in order to ascertain their agronomic, culinary and physico-chemical qualities and identify potential varieties.

Key words: Combining ability, earliness, gene action, grain yield, grain quality, *Oryza sativa*

CHAPTER ONE

INTRODUCTION

1.1 Background information

Rice is the most extensively grown crop and the second most valued crop after maize in the world today (Syed and Khaliq, 2008). It is consumed by over 3.9 billion people globally (Kohnaki *et al.,* 2013). Rice is intensively cultivated in Asia, and Asians consume about 75 % of the global rice supply indicating that rice is an important food security crop in the Asian countries (Dogara and Jumare, 2014).

Annual rice production in Africa was estimated at 31 million t from 11 million hectares under cultivation (FAO, 2017). Rice forms a larger part of the diet for both urban and rural populations in Kenya. Kenya produces about 140,000 metric t against a demand of over 540,000 metric t per year (MoA, 2014).

1.2 Importance and nutritional composition of rice

Rice supplies more than 70 % of the daily energy intake in some Asian countries like Myanmar, Laos, Cambodia and Bangladesh. In China and India, rice consumption declines to about 40 % because most people in Northern parts consume more wheat than rice (Dogara and Jumare, 2014). Popularity of rice is attributed to the fact that it is easily digested and has a short cooking time (Juliano, 1993). Rice has become the fastest growing source of food in Africa (WARDA, 2012). Rice grain provides considerable amounts of carbohydrates and proteins. It is mainly eaten in the form of whole grains (Norman and Kebe, 2004). Norman and Kebe (2004) reported that rice supplies more energy and protein than maize, sorghum or cassava. It is normally prepared by either boiling in water or steaming, and is eaten with beans, meat, fish or vegetables. Rice is a nutritious cereal crop that provides substantial amounts of nutrients essential for human dietary intake. However, rice has low amounts of riboflavin, thiamine, iron and calcium (Tripathi *et al.,* 2011).

1.3 Global rice production and trends

Globally, rice is grown on 163 million hectares with an annual yield of about 753 million t (FAOSTAT, 2017). China is the leading rice producer with an estimated 208.5 million t followed by India with 163.7 million t, Indonesia with 72.7 million t, Bangladesh with 52.1 million t, Vietnam with 43.6 million t, Thailand with 32.6 million t and finally Myanmar with 28.5 million t (FAOSTAT, 2017) (Table 1.1).

Globally, India is the leading exporter of rice and it sells about 10 million t annually, followed by Thailand with 9.9 million t, Vietnam with 6.1 million t, Uruguay with 0.9 million t, the United States with 3.4 million t even though it ranks 11th in production (FAOSTAT, 2017). The leading importers of rice include; Brazil with 1.8 million t, Iran with 1.2 million t, Saudi Arabia with 1.2 million t, Iraq with 0.9 million t, Mexico with 0.7 million t, and Cuba with 0.6 million t annually (FAOSTAT, 2017) (Table 1.2).

Table 1.1 Global paddy rice production, 2012 to 2016.

Annual paddy production in million tonnes			
Country	**2012-2014 (Average)**	**2015**	**2016**
China	206.5	209.8	208.5
India	158.7	156.6	163.7
Indonesia	70.4	73	72.7
Bangladesh	51.2	52.5	52.1
Vietnam	44.3	45.2	43.6
Thailand	35.5	27.4	32.6
Myanmar	28.1	27.5	28.5
Dominican Republic	0.9	0.9	0.9
Brazil	11.8	12.4	10.6
USA	9.3	8.8	10.2
EU	3.0	3.0	3.0
Australia	1.0	0.7	0.3

Source: (FAOSTAT, 2017)

Table 1.2 Global paddy rice imports, 2012 to 2016.

Rice imports in million tonnes, milled basis			
Country	**2012-2014 (Average)**	**2015**	**2016**
Iran	1.6	1.3	1.2
Iraq	1.3	1.0	0.9
Philippines	1.2	2.0	0.7
Saudi Arabia	1.3	1.6	1.2
United Arab Emirates	0.7	0.8	0.9
Mexico	0.6	0.6	0.7
Cuba	0.4	0.5	0.6
Brazil	1.6	1.6	1.8
United States of America	0.7	0.8	0.8
Russian Federation	0.2	0.2	0.2

Source: (FAOSTAT, 2017)

The United Nation (UN) reported that the world population will increase from 7.8 billion at present to over eight billion by the year 2025. Therefore, global rice production must be intensified from 753 million t at present to 758.8 million t by 2020 (Dogara and Jumare, 2014). Food and Agricultural Organization (FAO) reported that the world rice requirement by 2050 will be 943.6 million t which requires annual increase of about 5.8 million t from the present level of production. To meet 943.6 million t level of production by 2050 while utilizing the existing land resources, high yielding upland rice varieties with durable resistance to both abiotic and biotic stresses are required to achieve this target (Dogara and Jumare, 2014).

1.3.1 Rice production in Africa

Rice is a staple food for most people living in the East, West, Central and Southern Africa (Eric, 2010). The annual demand and production of rice in Sub-Saharan Africa is estimated at 8 and 6.2 million t respectively while the annual population growth in the region is estimated at 2.6 % (Norman and Kebe, 2004). The increasing demand of rice in Sub-Saharan Africa is attributed to increasing population, urbanization as well as the relative ease of preservation and cooking (Macauley and Ramadjita, 2015). Production and consumption of rice in Africa has been increasing at an estimated rate of 5.1 % and 6 % per year since 1970s. About 70 % of growth in production is attributed to increased area under rice cultivation, and 30 % increase was as a result of growing rice varieties with high yield potential (Norman and Kebe, 2004). The quantity of rice produced in Africa is insufficient and does not meet the demand of the increasing population (Macauley and Ramadjita, 2015). In the year 2012, the quantity of rice consumed annually was estimated at 24 million t in Sub-Saharan Africa. Local production accounted for about 60 % of the domestic consumption. Africa imports an estimated 3 million t yearly, which is equivalent to 25 % of the total global rice imports annually (Norman and Kebe, 2004). Paddy yield in West Africa is estimated 14.0 million t from 6.6 million hectares. Average paddy yield in this region is estimated at 3.0 t ha^{-1} (FAO, 2017). Nigeria leads in paddy rice production with total production of 6.7 million t followed by Mali with 2.2 million t, Guinea with 2.0 million t, Sierra Leone with 1.2 million t, Senegal with 559,000 t, Burkina Faso with 348,000 t and Benin with 234,000 t (FAOSTAT, 2014).

In North Africa, Egypt is the leader in paddy rice production with yield of about 6.0 million t from 462,000 hectares. Sudan produces about 16,900 t from 15,618 hectares with an estimated grain yield of 3,800 kg ha^{-1} (FAOSTAT, 2014).

Southern Africa has an aggregated rice production of 4.7 million t with Madagascar producing 4.1 million t, Mozambique (365,000 t), Malawi (120,000 t) and Zambia (26,000 t). Average paddy yield in Southern Africa is estimated at 2.6 t ha^{-1} (FAOSTAT, 2014).

Tanzania is a leader in paddy rice production in Eastern Africa with a total of 2.6 million t, and followed by Uganda (237,000 t), Ethiopia (132,000 t), Kenya (129,000 Mt) (Mwaniki et al., 2015) and Rwanda (97,000 t). Average paddy yield in Eastern Africa is estimated at 2.8 t ha^{-1} (FAOSTAT, 2014) (Table 1.3).

Egypt is the only exporter of paddy rice with an estimated 0.3 million t annually (FAO, 2017). The leading rice importers in West Africa include, Nigeria with an estimated 2.5 million t, and followed by Cote d'Ivoire with 1.4 million t, Senegal with 1.2 million t, Ghana with 620,000 t and Guinea with 500,000 t annually. In Southern Africa, South Africa is the main importer with 830,000 t followed by Madagascar with 400,000 t annually (Table 1.4).

Table 1.3 Paddy rice production in Africa, 2012 to 2016.

	Annual paddy rice production in million tonnes		
Country	**2012-2014 (Average)**	**2015**	**2016**
Egypt	6.1	5.9	6.3
Cote d'Ivoire	0.8	0.9	0.8
Guinea	2.0	2.0	2.2
Mali	2.1	2.3	2.8
Nigeria	4.7	4.8	5.0
Sierra Leone	1.2	1.0	1.1
Tanzania	2.2	3.0	3.4
Madagascar	4.0	3.7	3.8
Mozambique	0.4	0.4	0.3

Source: (FAO, 2017)

Table 1.4 Africa paddy rice imports, 2012 to 2016.

	Rice imports in million tonnes, milled basis		
Country	**2012-2014 (Average)**	**2015**	**2016**
Cote d'Ivoire	1.3	1.4	1.4
Nigeria	3.3	2.2	2.2
Senegal	1.2	1.4	1.1
South Africa	1.0	0.9	0.8

Source: (FAO, 2017)

1.3.2 Rice production in Kenya

Rice is the third staple diet after maize and wheat for most Kenyans living in rural and urban areas. It is mainly grown by smallholder farmers under irrigated lowlands or rainfed ecosystems as a commercial or food crop (Kimani et al., 2011). The major rice growing regions include; Central, Eastern Kenya, Lake Basin and the Coastal region (MoA, 2014). Rice production is estimated at 140,000 metric t against consumption of between 540,000 and 600,000 metric t (Ngotho, 2017). In Kenya, 95 % of the rice is cultivated under irrigation in paddy schemes and managed by the National Irrigation Board (NIB) and the remaining 5 % is grown in rainfed ecosystem (MoA, 2014). Average yield under irrigated lowland ecosystem is estimated at 3 t ha^{-1} and 5.6 t ha^{-1} for aromatic and non-aromatic rice variety (MoA, 2014). Rice consumption has been increasing at a rate of 12 % since 2008 while maize the staple food is at 1 % and wheat at 3 % (Ngotho, 2017). The increase in consumption is attributed to increasing incomes among the middle class, urbanization and busy life styles (Ngotho, 2017).

1.3.3 Rice production in South Sudan

Rice is the staple diet for an estimated 1.8 million people of the total population of 11.4 million people living in South Sudan. Cereal area per household is estimated at 0.9 hectares and sorghum being the main crop accounts for 69 % of the area sown followed by maize with 27 % while rice accounts for only 4 % of the area under cultivation with an estimated yield of about 0.6 t ha^{-1} (FAO, 2013). There is no data on total area under paddy rice cultivation, annual yield as well as trend of rice production in South Sudan (FAOSTAT, 2014). Dorosh and Rashid (2015), who conducted a survey in South Sudan, reported monthly consumption percentages of 85 % for sorghum, 33 % for wheat, 30 % for maize and 15 % for rice. Rice is mainly grown by smallholder farmers on a cropland size of about 0.32 hectares (Dorosh and Rashid, 2015). The smallholder farmers produce insufficient quantity of rice and do not meet the demand of the increasing population hence the demand gap is fulfilled by importing rice from the neighbouring countries. Diao et al., (2012) reported an estimated imported quantity of about 38 % and 71 % in 2009 and 2013 from Uganda

1.3.3.1 Rice agro-ecology and soil characteristics

In South Sudan, upland rice is mostly cultivated in the green belt region that covers the Southern parts of Yei, Maridi, Yambio and Tombura Counties. Annual rainfall varies from 800 to 2000 mm distributed over 6-9 months. Rainfall is bimodal, and it is divided into long rains between April and June and short rains between July and November. The temperature ranges from 25 to 40^{o}C. The crop growing season ranges between 100 to 200 days (FAO, 2013). The soil type is characterized by a mixture of ferrasols and sandy loam soils.

Rice performs well in the dark reddish-brown sandy loam soils found in the green belt region. The vegetation is mostly broad leaf woodland savanna comprising of both annual and perennial plants (FAO, 2013).

1.3.3.2 Rice cropping system

Smallholder farmers in Eastern Africa mainly grow indica rice varieties either in an upland rainfed or irrigated lowland ecosystem. Most of the smallholder farmers in Kenya grow lowland rice varieties and the water for irrigation is conveyed using partially lined canal and distributed through earthen canals. The farmers grow rice as a sole crop (KARI, 2000). In contrast, Farmers in South Sudan mainly grow indica rice varieties in an upland rainfed ecosystem with an average cropland size of 0.32 hectares (Dorosh and Rashid, 2015). Most farmers intercrop rice with maize to optimize their use of resources, while others practice rotation with other cereals like wheat, maize and high value crops like sweet potato, legumes and cassava (Dorosh and Rashid, 2015).

1.3.3.3 Rice varieties grown in Eastern Africa

Rice varieties in Kenya perform well at an altitude range of 0 to 1700 meters. They require a temperature range of 17^{o}C to 34^{o}C. The upland rice varieties cultivated include; NERICA 1, NERICA 4, NERICA 10, NERICA 11, TGR-94, Nam Roo and Dourado precoce. The irrigated rice varieties are Basmati 370, Basmati 217, BW196, IR 2793-80-1, ITA310 and Sindano (KARI, 2000) (Table 1.5). In contrast, the upland rice varieties cultivated in South Sudan include, NERICA 4, NERICA 1 and NERICA 10. These NERICA varieties were imported from Uganda either on individual basis or by humanitarian organizations and distributed to farmer groups for cultivation. However, some farmers in rural areas grow traditional rice cultivars of unknown origin and have not been characterized. The NERICA varieties were preferred because of their relatively good yield potential (1 to 2 t ha^{-1}), earliness (approximately 120 days to maturity), and average height of 100 cm making harvesting easier. However, its consumption is low due to the slight aroma, medium grain length and their cooking qualities are not as good compared to the long grain Pakistan rice sold in the market (Dorosh and Rashid, 2015).

Table 1.5 Rice varieties grown in Kenya and their characteristics.

Variety	Year released	Ecology	Yield	Characteristics	Region grown
NERICA 1	2009	upland	2.5-5 t ha^{-1}	Aromatic, short awn, high protein content (25 %), weed smothering ability, tolerant to rice blast RYMV, bacterial leaf blight, earliness (90 days) and good cooking quality	Western, Nyanza, Rift valley, Central, Eastern, Coast
NERICA 4	2009	upland	3.2-6 t ha^{-1}	Long grain, high protein content (25 %), weed smothering ability, high tillering ability, tolerant to rice blast RYMV, bacterial leaf blight, medium maturing (120 days) and good cooking quality	Western, Nyanza, Rift valley, Central, Eastern, Coast
NERICA 10	2009	upland	3.5- 6 t ha^{-1}	Long grain, awned, purple pigmented, high protein content (25 %), early maturing (90 days), tolerant to rice blast RYMV, bacterial leaf blight and good cooking quality	Western, Nyanza, Rift valley, Central, Eastern, Coast
NERICA 11	2009	upland	3-5 t ha^{-1}	Drought tolerant, high ratoonability, poor exertion, high protein content (25 %), tolerant to rice blast RYMV, bacterial leaf blight, medium maturity (120 days) and good cooking quality	Western, Nyanza, Rift valley, Central, Eastern, Coast
Dourado precoce	2009	upland	2.3-5.5 t ha^{-1}	Awnless, tolerant to rice blast RYMV, bacterial leaf blight, late maturing (145 days) and good cooking quality	Western, Nyanza, Central
Nam Roo	2010	upland	5-7 t ha^{-1}	Red stem, tall and susceptible to lodging, tolerant to RYMV and late maturing (150 days)	Coast, Nyanza, Central, Western
TGR-94	2013	upland	3-4 t ha^{-1}	Long grains, medium maturing (125 days), tolerant to rice blast	Coast, Nyanza, Central and Western
Basmati 370	2009	lowland	3-5.5 t ha^{-1}	Aromatic, tolerant to RYMV, medium maturing (135 days) and good cooking quality	Coast, Nyanza, Central, Western
Basmati 217	2009	lowland	3-5.5 t ha^{-1}	Aromatic, tolerant to RYMV, medium maturing (135 days) and good cooking quality	Coast, Nyanza, Central and Western
BW196	2010	lowland	8-10 tha^{-1}	Resistant to blast, susceptible to RYMV, late maturing (150 days) and medium cooking quality	Coast, Nyanza, Central and Western
IR2793-80-1	2013	lowland	8.2 t ha^{-1}	Late maturing (150 days), good cooking, susceptible to blast and RYMV	Coast, Nyanza, Central and Western
ITA310	2010	lowland	6-7 t ha^{-1}	Late maturing (150 days), good cooking, susceptible to blast and RYMV	Coast, Nyanza, Central and Western
Sindano	2009	lowland	8 t ha^{-1}	Late maturing (150 days), poor cooking, susceptible to blast and RYMV	Nyanza, Central and Western

Modified from www.kalro.org/ricebank

1.3.2.3 Production constraints

Smallholder farmers at the rice growing regions of Kenya mostly grow local rice cultivars that have low yield potential (3 t ha^{-1}), late maturing (150 days) and highly susceptible to rice yellow mottle virus (Kimani, 2010). Rice blast is a major challenge to rice farmers and can cause 80 % yield losses. The low yield potential for some improved rice cultivars grown in irrigated lowlands and rainfed is due to water stress and climate variability which has led to increase in drought across the country (Ngotho, 2017). In addition, the limited number of research scientists and technicians has adversely affected up scaling of research activities in South Sudan. There are no properly established rice breeding programs to facilitate the production of certified seeds. Expansion and utilization of research land has been hindered by political decisions. Poor infrastructure, lack of storage facilities, pest and diseases as well as poor extension services affected rice production in South Sudan (Dorosh and Rashid, 2015).

1.4 Problem statement

The average cereal yield in South Sudan is estimated at about 0.95 t ha^{-1} with per-capita cropland size of 0.32 hectares (Dorosh and Rashid, 2015). This average yield of cereals is much lower than in Uganda where there is minimum use of tradable inputs (1.6 t ha^{-1}), as well as lower in places with disadvantageous agro-ecological conditions like Ethiopia (3 t ha^{-1}) and Kenya (2 t ha^{-1}) (Diao *et al.*, 2012). The rice yield in South Sudan is very low (0.6 t ha^{-1}) compared to a minimum of 2.13 t ha^{-1} produced in the Sub-Saharan region (Michael *et al.*, 2007). Rural and urban consumption of rice in South Sudan is estimated at 3.0 kg and 10.92 kg per person per year respectively (Dorosh and Rashid, 2015), compared to 45 kg per-capita consumption in Sub-Saharan Africa (Muthayya *et al.*, 2014). The per-capita consumption in South Sudan is much lower than in most of the East African countries because the supply of locally produced rice is low. This is because smallholder farmers in South Sudan grow landraces that are low yielding, late maturing and of poor grain quality (FAO, 2013). In addition, the landraces are highly susceptible to rice yellow mottle virus and rice blast and this greatly contributes to decline in yields (Maurice, 2012). Much of the rice grains traded in South Sudan are imported from Uganda and North Sudan resulting in higher food prices for the local population (FAO, 2013), with an estimated imported quantity of 71 % (Diao *et al.*, 2012). Most of the rural poor cannot afford to purchase the imported rice on regular basis. Therefore, developing high yielding rice varieties with durable resistance to major diseases, earliness and high grain quality will improve productivity, increase proportion of locally produced affordable rice and contribute to food and nutritional security in Eastern Africa.

1.5 Justification

The demand for rice has been increasing at a rate of 12 % since 2008 in Eastern Africa. However, local production is very low to meet the demand of the increasing population (Ngotho, 2017). The demand gap is created because smallholder farmers in the rice growing regions of Kenya and other East African countries prefer growing lowland rice to upland rice. Upland rice varieties are marginally practiced because they have low yield potential, late maturing and have poor cooking and eating characteristics (Kimani, 2010). Therefore, improving the yield potential, earliness and grain quality of upland rice varieties through hybridization of indica and japonica rice may be a more sustainable way of increasing rice productivity in eastern Africa. Indica and japonica rice variety are sub-species of *Oryza sativa*. The gene pool of indica variety is characterized by long and slender grain, high amylose content (25-30 %), high in aroma but low yielding, late to medium maturity and resistant to pest and diseases (Golam *et al.*, 2011). However, Japonica variety has short and round grain, low amylose content (0-20 %), non-aromatic, high yielding and early maturing but susceptible to pest and diseases (OECD, 1999). Determining the general and specific combining ability in the indica and japonica lines is important because it shows the importance of non-additive and additive gene action in the expression of agronomic and yield traits (Sathya and Jebaraj, 2015).

1.6 Overall Objective

To increase rice productivity through the development of high yielding and locally adapted rice varieties combining earliness and high grain quality

1.6.1 Specific Objectives

1. To determine the combining ability and heterosis for agronomic and yield traits in indica and japonica rice crosses
2. To evaluate the existing $F_{2.3}$ families for yield potential, earliness and grain quality

1.6.2 Null hypotheses

1. Additive and non-additive gene actions are not significant in the expression of agronomic and yield traits
2. Rice genotypes with tremendous yield potential and high grain quality do not exist among the $F_{2.3}$ families

CHAPTER TWO

LITERATURE REVIEW

2.1 Taxonomy and Botany

Rice belongs to the grass family known as Gramineae (Dogara and Jumare, 2014). It is grown as a monocarpic annual plant; however it can also grow as a perennial plant producing a ratoon crop that can survive for about 20 years in the tropical areas (Boumas, 1985). Rice is considered an important crop in the tropical and temperate regions. Higher yields are obtained in the temperate zones than in the tropics (Wenela, 2013). Culm length varies from 1 to 1.8 m or more depending on the type of variety grown and the fertility of the soil (Boumas, 1985). Rice plant bears long and slender leaves ranging between 50 and 100 cm long and the width of the leaves range between 2 and 2.5 cm (Tripathi *et al.*, 2011) (Fig. 2.1).

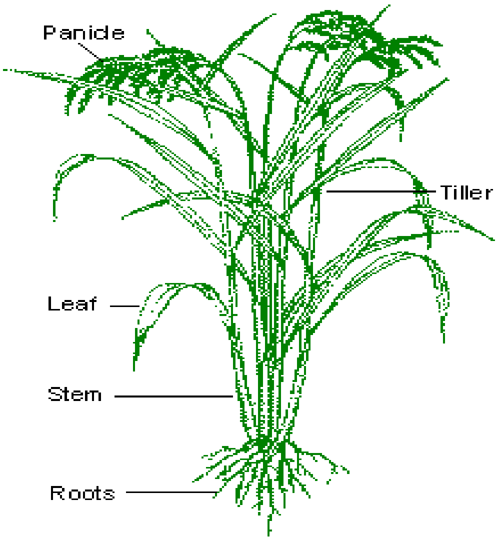


Figure 2.1 General morphology of rice plant (Chang *et al.*, 1965)

The jointed stem of rice called a culm consists of several nodes separated by the internodes at a distance of 1 cm at the base and further apart towards the tip of the rice plant. The node consists of a leaf and a bud. Mature internodes are hollow and finely grooved. Internodes at the lower part of the culm are short and thickened into a solid section (Tripathi *et al.*, 2011) (Fig. 2.2).

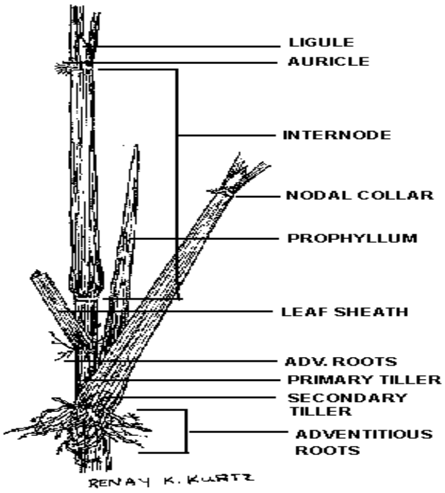


Figure 2.2 Parts of the rice culm (Chang *et al.,* 1965)

The rice plant has fibrous root system comprising of seminal, nodal and lateral roots. The seminal roots are sparsely branched and eventually die after seedling emergence and are immediately replaced by secondary adventitious roots (Chang *et al.,* 1965*)* (Fig. 2.3).

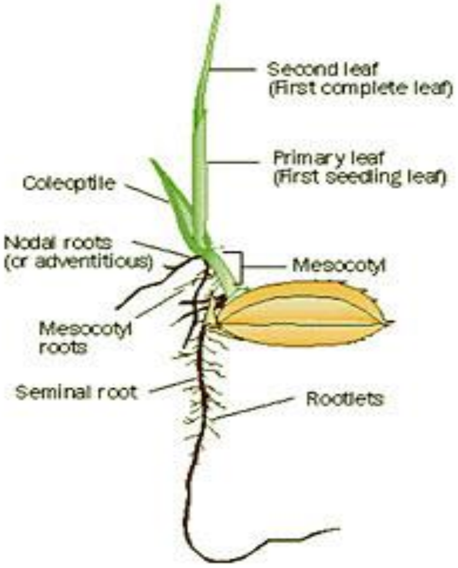


Figure 2.3 Parts of rice root (Chang *et al.*, 1965)

2.2 Floral organs

2.2.1 Panicle

The panicle is attached on a terminal internode of the culm. The solid base between the uppermost internode of the culm and the axis of the panicle is called the panicle base (neck). This node does not bear a leaf but may give rise to the first 1-4 panicle branches.

The ciliate ring at the base of the panicle is the dividing point when measuring panicle and culm length. The panicle has indeterminate branching where the nodes on the main axis give rise to primary branches which in turn carry the secondary branches that bear the pediceled spikelets (Fig. 2.4) (Chang *et al.,* 1965).

2.2.2 Rachis

Rachis is the primary axis of the inflorescence that extends from the panicle base to the tip. The rachis is continuously hollow except at the nodes where the branches of the panicle are attached (panicle pulvini) (Fig. 2.4) (Chang *et al.*, 1965).

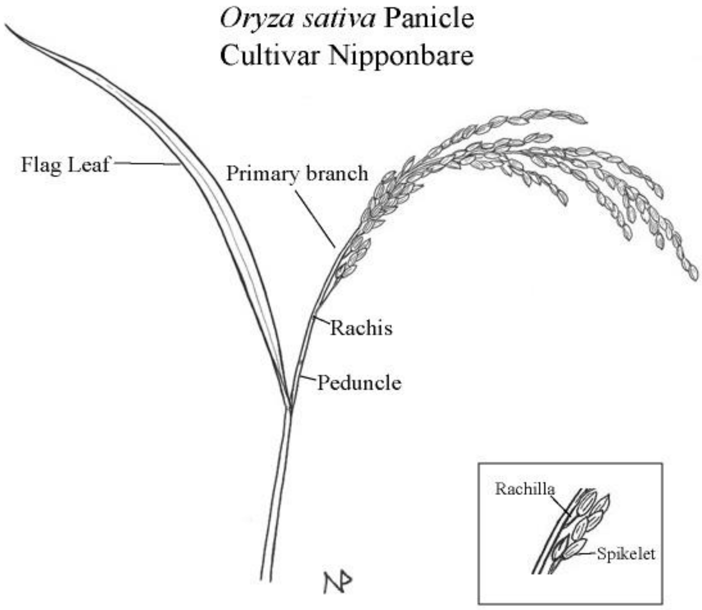


Figure 2.4 Component parts of panicle (Chang *et al.*, 1965)

2.2.3 Spikelet

A spikelet is a floral unit consisting of a rachilla on which a single floret is borne in the axils of 2-ranked bracets. The bracets of the lower pair of the rachilla are always sterile and are called sterile lemmas. The upper bracets (flowering glumes) consist of the lemma (fertile lemma) and palea. The lemma, palea and the flower form the floret (Fig. 2.5) (Chang *et al.,* 1965).

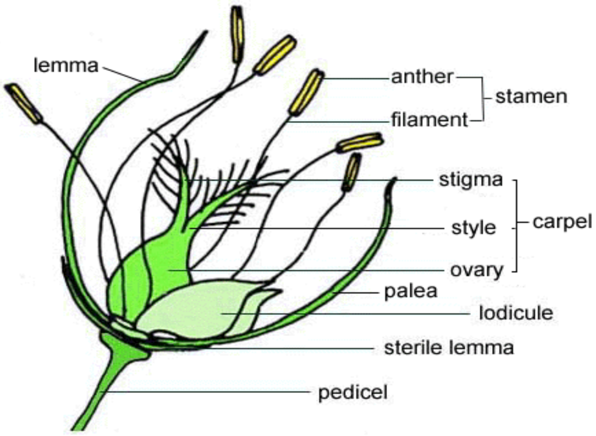


Figure 2.5 Parts of the spikelet (Chang *et al.*, 1965)

The rice grain comprises of outer protective covering, caryopsis and the hull. The seed coat comprises of six layers of cells with aleurone as the innermost layer. The embryo contains the embryonic leaves and is enclosed by the aleurone layer (Tripathi *et al.*, 2011). The endosperm comprises of starch granules embedded in a protein matrix, together with sugar, fats, crude fiber and organic matter. The hard protective coverings (hull or husk) comprises of 16-28 % of the total grain weight, pericarp weight range from 1-2 % and the aleurone, nucleus and seed coat range between 4-6 % (Fig. 2.6) (Xu-run *et al.*, 2014).

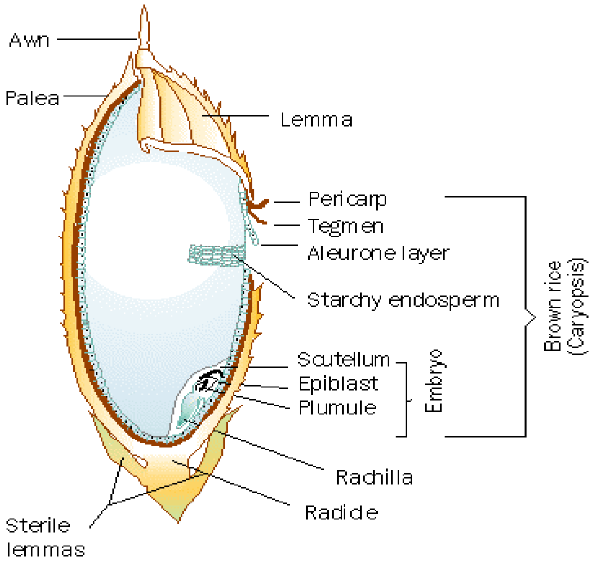


Figure 2.6 Parts of the rice grain (Chang *et al.*, 1965)

The grain ripening stages are classified into four stages: milky, dough, maturity and over ripe stage (Tripathi *et al.*, 2011) (Fig. 2.7).

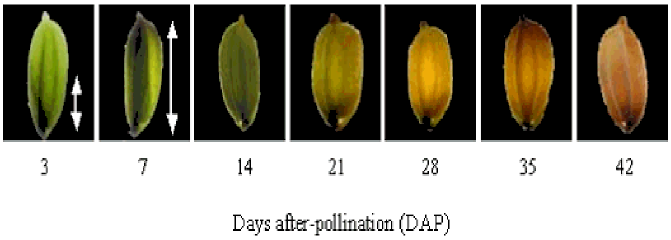


Figure 2.7 Grain ripening phase in rice: milky (3 to 7 d after pollination), dough (14 to 21 d), maturity (28 to 35 d) and over ripe stage (over 35 d) **(**Chang *et al.*, 1965).

2.3 Species of rice and the rice genome

The genus *Oryza* consists of 22 wild and two cultivated *(Oryza sativa* and *Oryza glaberrima)* species (2n = 24) with AA genome (Sanchez *et al.,* 2014) (Table 2.1).

Table 2.1 Genomic composition, chromosome number and distribution of *Oryza* species and their useful characters.

Species	**2n**	**Genome**	**Distribution**	**Characteristics**
Oryza sativa	24	AA	Worldwide	High yielding
Oryza glaberrima	24	AA	West Africa	Tolerance to drought, acidity, iron toxicity; resistant to blast, RYMV, BB, African gall midge, nematodes and smothers weeds
Oryza nivara	24	AA	Tropical and sub-tropical Asia	Resistant to grassy stunt virus and bacterial leaf blight
Oryza rufipogon	24	AA	Tropical and sub-tropical, Asia, tropical Australia	Resistant to blast, BB and tungro virus; tolerant to aluminium and soil acidity; increased elongation under deep water; source of CMS and yield enhancing loci
Oryza breviligulata/ Oryza barthii	24	AA	Africa	Resistant to bacterial leaf blight; tolerant to heat and drought
Oryza meridionalis	24	AA	Tropical Australia	Elongation ability; tolerant to heat and drought
Oryza	24	AA	South and Central	Elongation ability; source of CMS;

glumaepatula			America	tolerant to heat
Oryza punctata	48	BBCC	Africa	Resistant to bacterial leaf blight, leafhopper; tolerant to heat and drought
Oryza minuta	48	BBCC	Philippines and Papua New Guinea	Resistant to bacterial leaf blight and blast
Oryza officinalis	24	CC	Tropical and sub-tropical, Asia, tropical Australia	Resistant to blast, bacterial leaf blight, thrips, stem rot; tolerance to heat
Oryza rhizomatis	24	CC	Sri Lanka	Resistant to blast; tolerant to heat and drought
Oryza eichingeri	24	CC	South Asia and East Africa	Resistant to pests such as green leafhopper and brown plant hopper
Oryza latifolia	48	CCDD	South and Central America	Resistant to bacterial leaf blight, brown plant hopper; high biomass production
Oryza alta	48	CCDD	South and Central America	Resistant to striped stem borer; high biomass production
Oryza grandiglumis	48	CCDD	South and Central America	High biomass production
Oryza australiensis	24	EE	Tropical Australia	Resistance to brown plant hopper, blast, bacterial leaf blight; tolerant to heat and drought
Oryza granulate	24	GG	South Asia	Shade tolerance; adapted to aerobic soil
Oryza meyeriana		GG	Southeast Asia	Shade tolerance; adapted to aerobic soil
Oryza longiglumis	48	HHJJ	Jaya, Indonesia, Papua New Guinea	Resistance to blast and bacterial leaf blight
Oryza ridleyi	48	HHJJ	South Asia	Resistant to blast, bacterial leaf blight, stem borer, tungro virus and

				whorl maggot
Oryza brachyantha	24	FF	Africa	Resistant to bacterial leaf blight, yellow stem borer, leaf folder, whorl maggot; tolerant to laterite soil
Oryza schlechteri	48	KKLL	Papua New Guinea	Stoloniferous
Oryza coarctata	48	KKLL	Asian Coastal Area	Tolerant to salinity; stoloniferous

2.4 Pollination biology and cross ability

Rice flowers are self-pollinated because several factors hinder the receptivity of the stigma to out crossing. Fertilization takes place in the spikelet, which comprises of six stamens each containing over 1,000 pollen grains, and the carpel (containing the female parts) (OECD, 1999). During flowering, the spikelet opens and the pollen grains are shed on the surface of the stigma and later germinate (Tripathi *et al.*, 2011). The pollen tube then grows towards the egg cell to initiate double fertilization. Pollen and the ovule maturation are synchronized within the spikelet (OECD, 1999). The pollen grains of domesticated rice can survive on the anthers for about three to five minutes. In contrast the pollen of wild rice can survive on the anthers for up to nine minutes (Tripathi *et al.*, 2011). Most of the wild species of rice cross pollinate because they possess a big and extremely long stigma that protrudes to the exterior of the spikelet (OECD, 1999).

2.4.1 Intra-specific crosses

Natural out-crossing occurs at a rate of 5 % in the rice plant despite being a self-pollinated crop but this natural out crossing can be prevented by space and time (Tripathi *et al.*, 2011). Indica and japonica rice varieties are sub-species of *Oryza sativa* (Tripathi et al., 2011). Crosses within the indica or japonica gene pool tend to display high level of compatibility and results in high seed set, but inter-specific crosses between the two gene pools tend to exhibit high level of incompatibility and lower seed set. However, fertile F_1 hybrids can be generated from these two groups occasionally (OECD, 1999).

2.4.2 Inter-specific crosses

Oryza sativa and *Oryza glaberrima* have some similarity as a result of co-evolution, but natural hybrids between these two rice species rarely occur in nature. However, artificial crosses between these two groups through conventional breeding led to development of NERICA hybrids (Sarla and Swamy, 2005). The hybrids generated were highly pollen sterile, although a large proportion of their embryo sacs appear normal and functional (OECD, 1999). Crosses between *Oryza rufipogon,* the wild progenitor of *Oryza sativa* with *Oryza sativa* is possible but in some cases the F_1 tend to produce a mixture of wild and cultivated plants growing in the field but their F_1 progenies generated were fertile (OECD, 1999). Crosses between *Oryza glaberrima* and its wild progenitor *Oryza breviligulata* tend to generate prolific F_1 progenies and a natural mixture of wild and cultivated rice plants in the paddy fields. These hybrids tend to show similarity in most of their agronomic characters and also display annual growth habit (OECD, 1999). Wild rice comprises of geographical races such as Asian, African, American and Oceanian. These species share the AA genome, but the differences between them are due to F_1 pollen sterility (OECD, 1999). However, most of the *Oryza longistaminata* plants vigorously grow in paddy fields and tend to generate plants that are highly compatible with *Oryza sativa* (Tripathi *et al.,* 2011). This is attributed to the transfer of genes from rice cultivars across the reproductive barriers. *Oryza sativa* is compatible with wild species containing the BB, BBCC, CC, or CCDD genome than with the distantly related species with EE and FF genome. However, the progenies generated are highly male and female sterile (Tripathi *et al.,* 2011). OECD (1999) reported that hybridization between *Oryza sativa* and distantly related species like *Oryza ridleyi* and *Oryza meyeriana* were made but with low rate of success. Making crosses between distantly related species is possible but requires the use of embryo rescue technique in order to generate fertile F_1 hybrids and first backcross progenies (Tripathi *et al.,* 2011).

2.5 Origin and distribution of rice

Oryza sativa and *Oryza glaberrima* are the two domesticated species of rice (Dogara and Jumare, 2014). *Oryza sativa* originated from the river valleys of Yangtze and Mekon rivers of China (Tripathi *et al.,* 2011), while River Niger Delta in West Africa was the centre of origin for *Oryza glaberrima* (Dogara and Jumare, 2014). *Oryza sativa* is widely cultivated in Europe, Asia, South and North America, Middle East and Africa (Tripathi *et al.,* 2011). However, *Oryza glaberrima* is only cultivated in West African countries on a limited scale (Dogara and Jumare, 2014).

2.5.1 Cultivated rice varieties in Africa

Both *Oryza sativa* and *Oryza glaberrima* and their inter-specific hybrids are cultivated in Africa. New Rice for Africa (NERICA), Ofada rice and Ekpoma rice are the major types of rice grown in Africa. NERICA hybrids were created by hybridizing *Oryza glaberrima* and *Oryza sativa* (Sarla and Swamy, 2005). NERICA hybrids exhibit heterosis and show an improvement in grain head size from an estimated 75 to 100 grains per panicle to 400 grains per head. They express high yield potential from an initial yield of 1 to 2 t ha^{-1} to as high as 5 t ha^{-1} with use of fertilizers. NERICA hybrids also possess more protein (2 %) compared to their African or Asian counterpart (1.8 %). They grow to a reasonable height hence making harvesting easier than the *Oryza sativa* varieties (Sarla and Swamy, 2005). *Oryza glaberrima* is characterized by low yield potential and poor milling quality because the grains easily crack. These characters render *Oryza glaberrima* unsuitable for cultivation than *Oryza sativa*. However, *Oryza glaberrima* is tolerant to toxic levels of iron, drought, and low soil fertility as well as to fluctuation in water levels in the paddy fields. In addition, *Oryza glaberrima* is also resistant to major biotic stresses, including resistance to nematodes, midges, viruses and Striga (Sarla and Swamy, 2005).

2.6 *Oryza sativa* ecotypes

Japonica rice is mostly cultivated in the Eastern and Northern parts of China and also in other parts of the world. Sarla and Swamy (2005) reported that japonica rice varieties are well adapted to the cooler areas of the subtropics as well as the temperate zones. Japonica varieties are generally short plants with dark green and narrow leaves, with high tillering ability. Their kernels are bold and round. They are resistant to shattering but with low amylose content (0-20 %) (Tripathi *et al.,* 2011).

Javanica is extensively cultivated on the highlands of Cordillera Mountain in Philippines (OECD, 1999). Javanica rice varieties are tall in height with broad and light green leaves. Their kernels are thick, long and broad with low shattering ability but contains low amylose content (0-20 %) (Tripathi *et al.,* 2011).

Indica rice varieties are intensively cultivated in both the tropics and subtropics regions of the Philippines, India, Java, Pakistan, Indonesia and Sri Lanka as well as at the central and southern parts of China (Tripathi *et al.,* 2011). Indica rice varieties are tall with broad light green leaves, they have long and slender grains with high amylose content (25-30 %) but the grains have a high shattering ability (Sarla and Swamy, 2005).

2.7 Rice habitats and their hydrological conditions

Rice is grown in four types of environments including: irrigated ecosystem, rainfed lowland ecosystem, deep water ecosystem and upland ecosystem (Bouman *et al.,* 2007).

Irrigated rice ecosystem is widespread and covers about 55 % of the overall rice production area (Tripathi *et al.,* 2011). Dogara and Jumare (2014) reported that the irrigated rice ecosystem is more productive and accounts for over 75 % of the global rice production. The high productivity in the irrigated ecosystem is because the paddy fields are fertile with good drainage and are not prone to flooding or drought (Bouman *et al.,* 2007). The irrigated rice ecosystem requires more fertilizer application than the other rice growing environments. Therefore, farmers invest highly in this system in terms of purchase of fertilizers and their investments are profitable because losses due to flooding or drought stress are low (Dogara and Jumare, 2014).

In the deep water rice ecosystem, rice plants are flooded to a height of more than 50 cm during the entire rainy season (Bouman *et al.,* 2007). In this ecosystem, the rice seeds are planted a few weeks earlier before the rain starts (Dogara and Jumare, 2014). The rice seedling will suffer from drought for the first two weeks of growth, but when rain starts the water levels will rise for the entire crop growing season and the rice culm will increase in length of up to 3 m in response to rise in water level (Dogara and Jumare, 2014). The deep water rice ecosystem accounts for only 8 % of the global rice production area with a production of less than 2 t ha^{-1}.

In rainfed lowland rice ecosystem, the rice crops depend entirely on rainfall and do not receive irrigation (Bouman *et al.,* 2007). In the lowland rice fields, dikes and bunds are constructed around the rice fields in order to capture and conserve the rain water for crop growth and development (Dogara and Jumare, 2014). The variability in rainfall patterns can either cause flooding or drought in the rainfed lowland rice fields (Dogara and Jumare, 2014). Tillage is done when the fields are wet (Bouman *et al.,* 2007). This leads to build up soil hard-pan below the soil surface and the hard-pan formed hinders water seepage, thereby allowing water to accumulate in the field.

Rainfed upland rice ecosystem is predominant in the tropical climate areas mainly on flat land or mountain slopes. This rice ecosystem accounts for about 12 % of global rice production area and is generally low yielding (1.5 t ha^{-1}) than other rice ecosystems due to rainfall variation and distribution in the upland rice fields (Dogara and Jumare, 2014). Upland rice fields are bigger and highly mechanized than other rice growing environments (Dogara and Jumare, 2014). Upland rice varieties with high yield potential and better responsiveness to fertilizers were generated in Brazil, at IRRI and in Africa (Bouman *et al.,* 2007).

2.8 Rice grain quality

The end users are normally responsible for determining rice grain quality and they usually demand the best and affordable quality. Wenela (2013) reported that rice grain quality is influenced by the genotype of variety, rice growing environment, methods of processing and harvesting of the rice plant. Rice varieties with good milling qualities are highly desired by rice millers while the end users look at the cooking and eating characteristics of the rice grain (Tuano *et al.,* 2011).

2.8.1 Grain dimension of rice

Grain length, width and grain weight are the common parameters used to determine the physical qualities of rice (IRRI, 2000). Grain length is classified into three groups, namely long grain (6.61 to 7.50 mm), intermediate (5.51 to 6.60 mm) and short grain (less or equal to 5.50 mm). Arborio rice variety is high in grain width while basmati rice grains are greater in length (Adu-kwarteng *et al.,* 2003). The grain length of rice is determined by measuring the grain length and grain width using a vernier caliper. The grain shape of a rice variety is usually determined by calculating the length to breadth ratio of the rice grain, while the grain weight provides details of the size and density of the rice grain (Dela Cruz *et al.,* 2002). Kaul (1970) indicated that consumers mostly prefer long grains of over 6 mm and a grain shape ranging from 2.5 to 3.0 is widely accepted. Preference for grain shape and size differs from one region to another (IRRI, 2000). Other consumers desire short and bold grains while others prefer medium grains. Consumers in Indian sub-continent regions prefer long slender grains while consumers from South Asian regions prefer medium short grains (Dela Cruz *et al.,* 2002). Consumers in Africa prefer aromatic white long and slender rice grain (Anang *et al.,* 2011). Aromatic, long slender grains with soft cooked texture are preferred by consumers in South Sudan (Dorosh and Rashid, 2015). Dela Cruz *et al.,* (2002) reported that the long rice grains are highly preferred at the international market.

Singh *et al.,* (2000) analyzed the physico-chemical characteristics of some rice hybrids. They reported that the grain length of milled rice varied between 4.53 and 5.07 mm. Grain width varied from 2.43 to 2.62 mm, while the grain shape varied between1.84 and 2.09.

Sagar *et al.,* (1988) investigated the grain length of both aromatic and non-aromatic rice cultivars in Pakistan. They observed that Basmati 6129 had the highest value (7.3 mm) for grain length while JP-5 rice variety had the lowest value of 5.8 mm.

2.8.2 Cooking and culinary qualities of rice

The whiteness of a rice grain, grain shape and physico-chemical characteristics like aroma, amylose content and gelatinization temperature influence consumer demand for rice worldwide (IRRI, 2000). The culinary qualities of rice can be influenced by the amount of amylose content in the rice grain, gel consistency and gelatinization temperature (Dela Cruz *et al.,* 2002). Juliano (1993) reported a strong correlation between gelatinization temperature and cooking time, but gelatinization temperature is negatively correlated with gel consistency (IRRI, 2000).

Luzi-Kihupi *et al.,* (2007) conducted a study in Tanzania to evaluate the cooking and the eating qualities of mutant lines obtained from irradiating a local cultivar. Five early maturing mutant lines and two controls, IR53234-27-1 and Supa were evaluated for their physical grain characteristics. They discovered that the grain appearance for all the rice genotypes was accepted by the taste panel. The panel rated Supa parent as the best, and SSD 7 as normal. Their results revealed significant variation for all the characters tasted except the taste of the cooked rice. Regression analysis revealed that aroma significantly contributed to the isolation of the rice quality while softness of the cooked rice and aroma determined the general acceptance by the panel.

Oko *et al.,* (2012) studied the culinary qualities of 15 landraces and five hybrids newly introduced in Ebonyi State Nigeria. They discovered that the five hybrids did not increase in size during cooking, while cv-China rice variety recorded maximum elongation value (3.2 mm), the variety E4197 was better in physical appearance but dissolved during cooking. They concluded that the landraces had good cooking qualities than the hybrids.

Lang *et al.,* (2013) evaluated 37 rice genotypes for high yield potential and grain quality traits, they discovered that OM7OL, Can-Tho 2 and Can-Tho 3 were good in grain quality. The quality attributes of these varieties could be exploited by rice breeders in order to meet the demand of rice markets.

Wenela (2013) studied the grain quality and acceptability of five new rice varieties at Kilombero District, Morogoro Region. The cooking time for the five varieties ranged from 19.34 to 24.14 minutes with NERICA1 variety having the shortest cooking time and TXD85 had the highest cooking time. The amylose content ranged from 15.03 to 27.25 %, while the gel consistency values varied from 37.33 to 84 mm with alkali spreading value ranging from 2 to 4. The results showed that NERICA varieties had higher amylose content, and based on sensory evaluation results TXD88 was preferred to other rice varieties because it had good aroma, milling quality but low in amylose content. TXD306, NERICA 4 and TXD88 varieties had intermediate gel consistency values implying that they are soft when cooked.

2.9 Aroma in rice

Flavour in rice is as a result of volatile and semi volatile compounds present within the rice grain. It is a desirable trait that fetches high price in the market today (IRRI, 2000). The increasing demand for aromatic rice in the global market has attracted the attention of rice breeders and made them to include aroma among their major objectives during development of improved rice varieties (Gaur *et al.,* 2016). Aroma is present in three categories of rice cultivars i.e. Group V (Sadri and Basmati), Group I indica (Jasmine), and Group VI tropical japonica. Aromatic rice cultivars originate from Group V, and are characterised by long (Basmati and Kataribhog), medium (Sadri) and very small grains (Nama Tha Lay) (Gaur *et al.,* 2016). Rice cultivars classified in Group I contain very few aromatic rice cultivars and they originate from Vietnam, Thailand, China and Cambodia while aromatic rice varieties in Group IV originate from China, Philippines and Indonesia (IRRI, 2000).

Gaur *et al.,* (2016) reported over 250 non-volatile and volatile compounds in both fragrant and non-fragrant rice varieties, and they found that 2-acetyl-pyrrolin (2-AP) was the sole contributor of the pop-corn like aroma in rice. Fragrant rice varieties are highly desired in other regions of Asia and they are sold at premium price in the international market (Dela Cruz *et al.,* 2002).

Rice varieties with distinct aroma are highly desired by the Middle East consumers and they have the perception that a variety devoid of aroma is like food without salt (IRRI, 2000).

To the contrary, consumers in Europe believe that presence of aroma in food may induce spoilage and contamination (Efferson, 1985), but in the near future, importation of fragrant Basmati rice to Europe will exceed 70,000 t per year (IRRI, 2000).

There is high demand for aromatic rice in Africa. They command premium prices in the market and their popularity is increasing throughout urban West Africa (Rutsaert *et al.,* 2013). Ghana was among the first countries to adopt cultivation of aromatic rice (Anang *et al.,* 2011). Consumers in Liberia prefer round grain rice with low amylose content specifically for making porridge because their grains stick together when cooked (Rutsaert *et al.,* 2013).

Buttery *et al.,* (1988) quantified the amounts of 2-AP in milled and un-milled rice varieties. They discovered that the concentration of 2-AP varied between 60 to 90 ppb in milled rice and ranged between 100 to 200 ppb in un-milled rice. This difference could be attributed to the role played by the surface layer constituents in the formation of cooked rice aroma. Champagne (2008) further discovered that rice cultivars with low protein content are strong in aroma compared to those with higher protein.

Crowhurst and Creed (2001) used a panel of consumers to determine the influence cooking methods on aroma of cooked rice sample. They noted that aroma was significantly associated with the pilaf method of cooking than the excess method. They concluded that draining process in excess cooking method led to the loss of volatile flavouring compounds in the rice sample.

Golam *et al.,* (2011) evaluated 39 advanced breeding lines and 12 popular aromatic rice cultivars for aroma and grain yield in Malaysian tropical environment. They observed that E36, Khau Dau Mali, E26 and E13 had high yield with strong aroma.

Anang *et al.,* (2011) studied the influential factors on consumer preference for various rice brands in the metropolis of Tamale, Ghana and the quality characteristics which affect prices. They chose the respondents randomly and interviewed 100 of them using a semi-structured questionnaire. The results showed that consumers paid higher premiums for aroma and source of rice (local or foreign).

Seraj *et al.,* (2013) evaluated 43 rice genotypes for aroma using sensory test in Bangladesh. They observed that 13 rice genotypes were strong in aroma, ten with moderate aroma, 15 genotypes had slight aroma while five were non-aromatic.

2.9.1 Inheritance of aroma

Aroma in rice was believed to be monogenic recessive (Ghose and Butany, 1952; Berner and Hoff, 1986). Previous researchers believed that aroma was monogenic dominant (Kadam and Patankar, 1938). However, recent studies on inheritance of aroma indicated 3:1 (non-aroma: aroma) segregation ratio implying monogenic and recessive gene control (Berner and Hoff, 1986; Vivekanandan and Giridharan, 1994; Lorieux *et al.,* 1996). Scientists have not yet agreed on the nature of inheritance of aroma in rice.

Lack of consensus among scientists could be due to different aromatic varieties used and also the complexity in the procedure of determining aroma in rice.

2.10 Heritability in rice

Heritability estimate in rice provides information about the amount of transmissible genetic variation out of the total variation and it determines response to selection (Ghosh and Sharma, 2012).

Heritability estimate is specific to a given population and environment (Bhadru *et al.,* 2012). Traits that are not influenced by environment have high heritability. Broad sense and narrow sense are the two types of heritability. Broad-sense heritability is the ratio of genotypic and phenotypic variance for the traits, while narrow-sense heritability is the additive genetic portion of the phenotypic variance. Heritability estimates combined with high genetic advance is an appropriate tool in predicting the resultant effect in selecting the best genotypes for yield and yield traits.

Li *et al.,* (1997) studied the genetic basis of 1000 seed mass, grain per panicle and grain weight per panicle of F_4 families generated between Lemont x cv.Teqing using fragment length polymorphism markers. The results showed that epistasis was dominant in yield traits with low heritability like grain mass per panicle and filled grains per panicle.

Reza *et al.,* (2010) studied heritability for yield and grain quality traits of $F_{2:3}$ families generated between Mousa-Tarom x 304. The results showed that narrow sense heritability of panicle length and culm length were low (<0.18) and was very high in grain quality traits such as grain length, grain width and grain shape (>0.84).

Rafii *et al.,* (2014) evaluated 12 F_1 hybrids and five checks for grain quality, yield and yield components. The results showed that plant height (99.8 %), panicle length (96.9 %) and grain shape (56.7 %) had the highest heritability values. These traits can easily be inherited to the next generation. Grain length, amylose content, grain weight per panicle and 1000 seed mass showed low values of heritability varying from 20.2 to 35.9 % implying that these traits were affected by the environment.

2.10.1 Combining ability in rice

Various biometrical techniques were designed to analyze genetic variability for yield and yield components (Comstock and Robinson, 1948; Griffing, 1956; Kempthrone, 1957; Kempthrone and Curnow, 1961). Combining ability in crosses refers to the ability of the parental genotypes to transmit certain combination of genes to their progenies during a hybridization program following a distinct mating design. Combining ability studies help in determining the general and specific combining ability of parents and their progenies involved in a hybridization program and leads to identification of better general combiners and good specific combinations (Fasahat *et al.,* 2016). The idea of general and specific combining ability has been greatly utilized by plant breeders. The mean performance of a genotype in a hybrid combination is called general combining ability and it is mainly attributed to additive gene action.

Specific combining ability is the deviation of the progenies from the mean value of the parental lines, and is due to dominant and epistatic gene actions (Fasahat *et al.,* 2016).

Satheesh *et al.,* (2010) studied the combining ability for yield and yield components in rice of seven females and four males using line x tester mating design. They reported higher GCA for pant height, filled grains per panicle, duration to 50 % flowering, number of effective tillers per plant 100 seed mass and grain yield implying the predominant role of additive gene action in the expression of these traits. The parents JAYA and CRAC 2221-67 were good general combiners for grain yield while the hybrid combinations CRAC 2221-67 x JAYA and IR6331-1-B-3R-B-24 x JAYA were the best specific combiners for grain yield.

Hasan *et al.,* (2013) studied the combining ability for grain yield and yield components of 70 F_1 progenies of rice developed by crossing seven cytoplasmic male sterile lines and 10 testers. They reported that SCA variance was higher than the GCA variance showing the dominance of non-additive gene action in the inheritance of these traits. The parents D Shan A and IR64R were good general combiners for dwarfness and earliness. The crosses BRR19A x BR168R and DShan A x BR168R were good specific combiners for grain yield.

Gnanamalar and Vivekanandan (2013) studied the combining ability for physico-chemical characteristics of seven high yielding rice genotypes and their 21 crosses generated using half diallel. The results showed higher GCA for 1000 seed mass, grain length and grain shape while higher SCA was recorded for milling percentage, grain yield, head rice recovery, hulling percentage, grain width, gel consistency, amylose content and alkali digestion value. The parents ADT 41 and AS 90033 were good general combiners for physico-chemical characteristics and grain yield, while the crosses CO 47 x Jeeragasamba, ADT 41 x ACM 98003, TKM 9 x Jeeragasamba, ACM 98003 x AS 90033 and CO 47 x TKM 9 were good specific combiners for physico-chemical characteristics and grain yield.

Bedi and Sharma (2014) studied combining ability of 15 F_1 progenies of rice generated using line x tester design with three lines including two checks. They reported greater SCA variance for sterile spikelets per panicle followed by number of fertile spikelets panicle^{-1}, percent pollen fertility, percent spikelets fertility, harvest index, leaf area index, grain yield per plant, plant height, chlorophyll content, length of flag leaf, 50 % days to flowering, 1000 seed mass, effective tillers and length of panicle indicating the dominance of non-additive gene action in the expression of these yield traits.

Malemba *et al.,* (2017) studied combining ability for drought tolerance of NERICA parents and 30 F_1 progenies developed using full diallel mating design. NERICA 15 and NERICA 2 were good general combiners for drought tolerance and grain yield while the hybrid combinations NERICA 2 x NERICA 15, NERICA 11 x NERICA 15, NERICA 1 x NERICA 15 and NERICA 15 x NERICA 2 were good specific combiners for grain yield under drought conditions. The review of combining ability above suggested that both additive and non-additive gene action are important in the inheritance of yield and yield components in rice.

2.10.2 Heterosis in rice

Heterosis refers to the superior performance of hybrids relative to their parents. It was initially observed by Jones (1926) who reported a significant increase in culm number and grain yield in some F_1 hybrids compared to their parents. Heterosis is divided into heterobeltiosis (the performance of a hybrid compared with that of the best parent in the cross), mid-parent heterosis (performance of a hybrid compared to the average performance of its parents), and standard heterosis (the performance of a hybrid compared with high yielding variety in the region) (Alam et al., 2004). Standard heterosis is more important of the two levels of heterosis because it is aimed at developing desirable hybrids superior to the existing high yielding commercial varieties (Chaudhary, 1984). Therefore, hybrids with the potential for commercial utilization should exceed the yield level of the standard check variety by 15 to 20 % (Swaminathan et al., 1972). Vanaja and Babu (2004) reported that increase in grain yield was due to favourable heterosis in yield characters like number of spikelets per panicle, flag leaf area and number of filled grains per panicle. Positive heterosis is desirable for grain yield and negative heterosis is preferred for earliness.

Rahimi *et al.,* (2010) studied heterosis for yield and yield components in 15 F_1 hybrids developed by half diallel cross of six diverse rice cultivars at Rashat, Iran in the cropping season of 2006. They reported significant standard heterosis for growth period (-24.4**), reproductive period (85.5**), flag leaf area (-45.6**), plant height (-8.3**), panicle length (-18.9**), number of panicles per plant (13.6*), filled grains per panicle (10.8**), 1000 seed mass (17.1**), grain yield (20.9**), brown grain length (5.2*) and brown grain width (13.5**). They observed highest heterobeltiosis in the hybrid Dorfak x Domsefid for grain yield (20.9**).

Soni *et al.,* (2011) studied heterobeltiosis for yield traits in 20 F_1 hybrids. They reported significant heterobeltiosis in the hybrids IR58025A x IRFAN-15, IR58025A x SR-6-SN-8, IR58025A x ETI-13, APMS6A x ET1-12 and APMS6A x NPTR-2 for grain yield and seven hybrids showed significant negative heterosis for earliness.

Tiwari *et al.,* (2011) studied heterosis involving 3 cytoplasmic male sterile (CMS) lines and 20 elite restorers following line x tester mating design. The results indicated that the heterobeltiosis for grain yield was superior for 43 hybrids and the value ranged from 11.63 to 113.04 %, forty six hybrids showed superiority over the standard check (Sarjoo-52) and the value ranged from 10.48 to 71.56 %. Most of the hybrids that exhibited hybrid vigour over the better parent or standard variety for grain yield also showed significant heterosis for number of fertile spikelets and number of spikelets per panicle.

Patil *et al.,* (2012) studied heterobeltiosis for yield and yield components involving four lines and ten testers generated using line x tester mating design. The results showed that 16 F_1 hybrids showed significant heterbeltiosis over better parent for grain yield per plant. The cross Sathi 34-36 x Lalkada, Sathi 34-36 x GR-6 and GR-5 x GR-6 were the best heterotic hybrids for grain yields per plant.

Borah *et al.,* (2017) studied the performance of 60 F_1 hybrids along with 23 parents and three standard checks at Assam Agricultural University in India. The results showed that mid-parent heterosis for grain yield varied from -88.7 % (IR-79156A x IET19916) to 151.5 % (IR58025A x Prafulla), heterobeltiosis from -91.9 % (IR-79156A x IET19916) to 128.2 % (IR58025A x Prafulla) and standard heterosis ranging from -91.3 – 56.5 % over the late maturing check Ranjit, -88.2 – 148.3 % over medium duration check TTB 404 and -91.9 – 44.4 % over the hybrid check JKRH 401.

2.11 Molecular breeding methods

Plant breeders use several breeding techniques to alter the behavior of an existing crop varieties, such techniques include; marker assisted approaches. This approach complements conventional breeding method and it facilitates early selection of specific combination of genes in a particular crop variety (Tanksley and McCouch, 1997; Rafalski, 2002; Hittalmani *et al.,* 2003; Zhou *et al.,* 2003). Alternatively plant breeders can also align particular traits by introducing foreign genes using transgenics (Ye *et al.,* 2000; James, 2003). Molecular markers have played significant role in rice cultivar improvement, screening, phenotyping and germplasm collection (Wang *et al.,* 2007). The application of molecular markers in rice breeding has been recently reviewed (Kumar *et al.,* 2009; Benali *et al.,* 2011). Several major genes were identified for rice blast and were targeted for mapping investigations using a number of marker systems and approaches (Ashkani *et al.*, 2014). DNA markers such as simple sequence repeats, single nucleotide polymorphisms, amplified fragment length polymorphisms, random amplified polymorphic DNAs and restriction fragment length polymorphisms were reported to be linked with blast resistance genes in rice (Ashkani *et al.*, 2014; Tanweer *et al.*, 2015). Scientists have used these DNA markers for genetic mapping to identify candidate genes and QTLs in many plant species (Askani *et al.*, 2015). Important genes that confer resistance to rice blast, bacterial leaf blight, brown planthopper, tungro and grassy stunt virus were successfully transferred from wild rice species into elite breeding lines of rice including QTLs for biotic and abiotic stress resistance (Brar and Khush, 1997).

Currently plant breeders are focusing on marker assisted selection instead of conventional breeding. Marker assisted selection reduces the time for phenotypic selection and saves the cost of selecting for a desired traits (Koide *et al.*, 2009). The common application of marker assisted selection is pyramiding of linked genes into a single cultivar or line (Askani *et al.*, 2015). Marker assisted backcrossing is another technique that is being used to develop blast resistant rice cultivars (Sundaran *et al.*, 2009) and is superior to conventional backcrossing in precision and efficiency (Askani *et al.*, 2015). Recent application of marker assisted backcrossing led to introgression of many blast resistance genes into genetic background and improved the blast resistance (Hasan *et al.*, 2015).

2.11.1 Transgenic rice

Genetically modified crops are currently grown in over 28 countries worldwide (Gupta, 2013). The area for growing genetically modified crops has increased tremendously from 1.7 million hectares in 1996 to 170 million hectares in 2012. Numerous insect resistant genes (*Bt* genes) were isolated from both plants and animals and have been successfully introduced to different rice varieties. The common *Bt* genes used include; *Cry1A, Cry1Ab, Cry1Ac* and *Cry1Ab/Ac* fusion gene (Bakshi and Dewan, 2013). The rice lines IR64, Pusa Basmati-1, Basmati 370, IR58, Minghui 63 and Shanyou 63 carry the *Bt* genes and they expressed resistance against yellow stem borer, leaf folder and striped stem borer (Bakshi and Dewan, 2013). The major issue is that, numerous insects developed resistance to *Bt* toxins in greenhouse conditions (Bates *et al.,* 2005). Therefore, development of transgenic rice varieties with a combination of several toxic genes with high level of expression needs to be a research priority (Maqbool *et al.*, 2001).

2.12 Correlation in rice

Correlation analysis in rice helps the plant breeder to indirectly select for traits that influence yield and it provides an understanding of yield components (Golam *et al.,* 2011). It is an essential tool for plant breeders before embarking on any rice breeding programme.

Correlation analysis indicates the magnitude of association between pairs of characters and forms the basis of selection index. Grain yield is an outcome of interaction of a group of interrelated and interdependence characters. Therefore, the knowledge of correlation studies in rice enables the plant breeder to understand how the improvement of one character brings a concurrent change in the other characters (Golam *et al.,* 2011).

Singh *et al.,* (2002) evaluated indica rice cultivars. They reported positive correlation between panicle lengths (r = 0.56*), days to maturity (r = 0.45*) and number of effective tillers per plant (r = 0.58**), 1000 seed mass (r = 0.38*) and filled grains per panicle (r = 0.52*) with yield while a negative correlation between filled grains per panicle and 1000 grain weight (r = -0.11*) was observed.

Zahid *et al.,* (2006) reported a negative correlation between numbers of effective tillers per plant (r = -0.23*), number of filled grains per panicle (r = -0.37*) and grain yield (r = -0.56*) with plant height.

Chakraborty *et al.,* (2010) reported a strong correlation between plant height, number of panicles per plant (r = 0.53**), panicle length (r = 0.53**), number of filled grains per panicle (r = 0.57**) and harvest index (r = 0.86**) with grain yield.

Golam *et al.,* (2011) studied correlations between yield and yield components of 53 rice genotypes comprising of 12 globally popular aromatic rice cultivars and 39 advanced breeding lines in Malaysian tropical environment. Two local varieties MRQ 50 and MRQ 72 were used as check varieties. They reported a strong correlation between number of fertile tillers (r = 0.69**), grain per panicle (r = 0.86**) and fertile grain per panicle (r = 0.65**) with grain yield.

2.13 Rice breeding goals

Increasing the yield potential of a crop is a major objective of any plant breeding program (Kumashiro *et al.,* 2013). However, the importance of breeding objectives of a rice crop can differ from one area to another (Tadele, 2017). Therefore, plant breeders need to ensure that their breeding goals must solve the existing problems in a particular rice growing environment while considering the specific desired traits of the rice variety as well as address the concerns of the rice farmers, millers, traders and consumers in the rice value chain (Kumashiro *et al.,* 2013).

2.13.1 Breeding for high grain yield

Increasing yield and productivity is the most important goal for almost all rice breeders in Africa and in the world. In Africa, traditional rice varieties have stable yields but with low yield potential (Kumashiro *et al.*, 2013). Plant breeders have placed more emphasis on increasing the yields of various rice varieties across multiple environments.

The first approach employed by plant breeders to increase grain yield of rice varieties include validation and incorporation of yield component QTLs detected elsewhere in other varieties and introduced into commercial rice varieties, this approach was successfully deployed at Africa Rice centre (Ando *et al.,* 2008; Obara *et al.*, 2010; Ookawa *et al.,* 2010). The second approach involves application of recurrent selection scheme designed to accumulate desirable combination of genes for yield through repeated cycles of recombination and selection (Gallais, 1990; Guimaraes, 2005). This approach was successful in Brazil and they achieved higher yields in upland rice ecosystem (Breseghello *et al.,* 2011). The last approach involves developing F_1 hybrid varieties that are well suited to rice environments. Hybrid rice was successfully developed in Asia, China and India. Africa Rice Centre started evaluating hybrid rice from China in 2009 and also developed a hybrid rice improvement program for irrigated lowland at the Sahel research station in Senegal (Kumashiro et al., 2013).

2.13.2 Breeding for resistance to biotic stresses

Biotic factors inflict heavy losses to field crops grown in Africa. This is attributed to the presence of favourable weather conditions such as temperature and humidity (Tadele, 2017). Goldman (1996) reported that yield of field crops in many African countries including Kenya and Nigeria have reduced tremendously due to the outbreak of pest and diseases. Yield losses due to insect damage vary from 30 % to 60 % in Africa (Oerke, 2006). Rich and Ejeta (2008) identified rice blast, rice yellow mottle virus and bacterial leaf blight as the most devastating rice diseases in Africa as well as grassy and parasitic weeds can cause tremendous yield losses in rice, maize, sorghum and millet.

Thiemele et al., (2010) conducted studies at African Rice Centre on rice yellow mottle virus. They identified a new resistance gene *rymv2* in *Oryza glaberrima.* Resistant BC_3F_5 lines are under evaluation for agronomic traits in multiple locations in Africa. In order to make the resistance to rice yellow mottle virus more durable, markers for *rymv2* are being introduced to breeding lines carrying the *rymv1-2* gene.

Sere et al., (2011) reported genes that conferred multiple resistances to rice yellow mottle virus, rice blast, bacterial leaf blight and African rice gall midge at African Rice centre. For breeding for resistance to rice blast, field resistant genes *Pb1* and *Pi21* were provided by NIAS, Japan, are being introduced in upland rice varieties (NERICA 1, NERICA 4 and FKR 43) and irrigated low land varieties (Sahel 108, NERICA L-19 and Kogoni 90-2).

Albar et al., (2006) identified germplasm (Gigante) with resistance to rice yellow mottle virus, in contrast Nwilene et al., (2009) reported germplasm with resistance to African rice gall midge.

2.13.3 Breeding rice for grain quality

Grain quality is considered an important aspect in meeting consumer demand for high quality food. It enables locally produced rice variety to compete favourably with the imported rice in the in the market (Fofana *et al.*, 2010).

Kumashiro *et al.,* (2013) reported that aromatic rice having long slender grain and with medium amylose content (20-25 %) is preferred by urban consumers and rice varieties with high amylose content (>25 %) are widely accepted in Nigeria.

AfricaRice (2010) developed three fragrant rice varieties including; Sahel 177, Sahel 328 and Sahel 329. They observed that Sahel 177 had high yield potential, Sahel 328 was early maturing and Sahel 329 was widely acceptable for its good grain quality.

2.13.4 Breeding for resistance to abiotic stresses

Abiotic stresses are climate and soil related constraints that cause huge crop yield losses in Africa. Vast areas in Africa have low soil fertility due to high weathering and leaching causing nitrogen and phosphorous deficiency (Okalebo *et al.,* 2006). Ndour *et al.,* (2016) revealed that poor soil management practices carried out by farmers such as burning of crop residues also contribute to decline in soil fertility. Drought is the main stress affecting crop production in Africa (Iqbal *et al.,* 2013). It accounts for over 40 % yield losses in rice. Drought has become more prevalent in southern Africa due to unreliable rainfall (Fauchereau *et al.,* 2003). Gazey (2016) reported that high concentration of aluminium in soils results in stunted plant growth and consequently reducing root growth, small grain size and poor crop yield. Goussard and Labrousse (2011) observed that most areas in Africa have become less productive as a result of soil acidity related to parent material and low retention of chemical fertilizers. Soil salinity affects crop productivity (Ndour *et al.,* 2016). Gale (2003) reported that a third of the global arable land is affected by salinity and about 5 % in Africa. Global warming is also detrimental crop production. Bita and Gerats (2013) reported that an increase of 3 to 4°C in air temperature causes yield losses of about 15 to 35 % both in Africa and Asia. Japan International Research Centre for Agricultural Sciences (JIRCAS) in collaboration with African Rice Centre conducted a drought research focusing on deep rooting in rice. They screened a total of 654 rice varieties and selected 17 rice varieties with deep roots. Tsunematsu and Samejima (2011) reported that research efforts to identify QTLs associated to drought resistance are still ongoing.

2.14 Rice breeding in Eastern Africa

2.14.1 Rice breeding in Kenya

In Kenya, about 80 % of the rice grown is under irrigation schemes established by the government while the remaining 20 % is produced under rainfed conditions (MoA, 2009). The irrigation schemes include; Mwea, West Kano, Bunyala and Ahero covering an area of 6,475, 602, 213 and 202 hectares respectively. The main challenge in the irrigated ecosystem is adequate supply of irrigation water to the paddy field when needed due to limited amount of irrigation water. Therefore, there is need for research on development of water saving rice cultivation technologies as one of the countermeasures to overcome the limitation in the amount of irrigation water supplied to the paddy field. The commonly grown rice cultivar (Basmati 370) at Mwea irrigation scheme is highly susceptible to rice blast. However, farmers continue to grow it because of its culinary quality and high market price (Kihoro *et al.,* 2013). NERICA was introduced in Kenya in 2003. Since then, NERICA adaptability trials have been conducted across the country (Atera *et al.,* 2011). Based on the trials, four upland NERICA varieties, namely NERICA 1, NERICA 4, NERICA 10 and NERICA 11 were selected for dissemination. The NERICA varieties have been used as breeding materials at public and private research stations because of their desirable traits such as; cold tolerance, water use efficiency under soil moisture stress conditions, plasticity in root development in response to soil moisture stress, deep rooting, tolerance to green rice leafhopper and useful weed traits like tolerance to *Striga* (Atera *et al.,* 2011). The new hybrid rice variety AT058, locally known as Atieno was bred by Western Kenya Afritec Seeds Ltd. Kenya Plant Health Inspectorate Services (KEPHIS) in collaboration with Afritec Seeds Ltd conducted farm trials at Mwea, Ahero and West Kano irrigation schemes. The results showed that AT058 hybrid variety yielded up to 35 bags of rice per acre, equivalent to 10 t ha^{-1} compared to between 15 to 20 bags produced by the traditional rice variety. The hybrid rice variety was registered by KEPHIS in 2017 and waiting official launching and release into the market in Kisumu, Migori, Kirinyaga, Busia and Homa Bay Counties (Dalton, 2017).

African Agricultural Technology Foundation (AATF) together with partners (Hybrids East Africa Ltd) is developing hybrid rice that has significant yield advantage of (9 to 10 t ha^{-1}) over Basmati 370 (3 t ha^{-1}) which is predominantly grown by rice farmers in Kenya. Over 180 hybrid lines including; PS-14K11140455 x AT049, PS-14K11140455 x AT013, PS-14K1114045 x AT030, PS-14K11140446 x AT036, PS-14K11140446 x AT030, PS-14K11140455 x AT014, PS-14K11140446 x ATO13, and PS-14K11140455 x AT042 are being evaluated at Mwea irrigation scheme (Muchiri, 2017).

2.14.2 Rice breeding in Uganda

Rice in Uganda is grown in the Eastern and Western parts of the Country due to the presence of lowland areas with high moisture throughout the crop growing season. NERICA rice was introduced in Uganda in 2002. NERICA adaptability evaluation across the country led to the adoption of NERICA 1, 4 and 10 varieties in addition to the traditional lowland varieties (Kibimba rice varieties) (Kikuchi et al., 2014). A research initiative which began in 2010 by research scientists at National Crops Resources Research Institute (NaCRRI), Namulonge in Uganda focused on breeding for biotic and abiotic stresses in upland rice varieties. They screened a total of 191 rice introductions from Africa and Asia. From the preliminary yield trials, a total of 660 hills of F_3 families were selected. From the 660 genotypes, 75 were selected for rainfed lowland and 65 were selected for rainfed upland. The candidate lines include; CAIAPO x CT16324-CA-9-M, WAB450-1-BL1-136-HB x WAB450-B-136-HB, CT16317-CA-4-M x WAB365-B-1H1-HB, IRAT325 x WAB450-B-136-HB and CT16342-CA-25-M x CK73 were among the lines selected for further evaluation. The second preliminary evaluation comprised of 84 lines of F_4 segregating population selected from the 660 F_3 families and planted at five sites across the country, namely Namulonge, Kigumba, Kibaale, Lira and Doho. The main stresses targeted include; rice yellow mottle virus, bacterial leaf light, leaf streak, rice blast, drought and narrow leaf spot. From the second trial, 20 promising lines showed resistance to rice blast, rice yellow mottle virus, and bacterial leaf light in all the sites. The promising lines were further tested in 2011 in two locations, namely Namulonge and Kibaale. Subsequently 12 lines were tested in 2012 A and 10 lines in 2012 B. The best six genotypes in terms of grain yield include; P27-H14 (11,950 kg ha^{-1}), P29-H4 (9,750 kg ha^{-1}), P36-H17 (9,313 kg ha^{-1}), P5-H1 (9,111 kg ha^{-1}), P36-H9 (8,688 kg ha^{-1}) and

P36-H4 (8,417 kg ha^{-1}). Six varieties namely NamChe-1, NamChe-2, NamChe-3, NamChe-4, NamChe-5 and NamChe-6 were presented to the variety release committee and were released in 2013 (Lamo et al., 2017).

In 2010, a team of research scientists at NaCRRI-Namulonge started conducting upland rice trials with 300 breeding lines using collection from Africa and Asia. The rice varieties from West Africa include WITA 9 rice varieties and two varieties from Tanzania (Komboka and Supa varieties) and others from International Rice Research Institute (IRRI 1 variety). Four new rice varieties namely; Okile, NERICA 6, IRRI 522 and GSR007 were released by the Plant Variety Release Committee at the Ministry of Agriculture in 2014 (Lominda, 2014). A new hybrid rice variety (Y'liangyou 900) was introduced from China in 2016 with the aim to replace the traditional lowland rice variety (Kaiso) which is mainly grown by Butaleja farmers at Butaleja District in Western Uganda. The Food and Agricultural Organization (FAO) is responsible for distributing the new rice hybrid. FAO has already trained 1,000 farmers on the new hybrid variety. Yield estimates are 3,000 kg per acre compared to the traditional cultivar (Kaiso) which gives between 1,000 to 1,500 kg per acre. The new hybrid variety has high yields, strong stems, resistant to blast, rice yellow mottle virus, good grain quality and fast maturing (130 to 140 days) (Yahudu, 2017). Uganda produces 100,000 tonnes but demand is 250,000 tonnes. Uganda intends to increase rice production to about 400,000 metric tonnes by 2018 by revising the land Act 1995, developing strategy of training more agricultural officers and rice farmers and through supply of high quality seeds to farmers (Yahudu, 2017).

2.14.3 Rice breeding in Tanzania

TXD 306 or SARO 5 is a high yielding (4 t ha^{-1}) rice cultivar developed in 2009 by Ifakara Research Centre, formerly known as the Kilombero Agricultural Research and Training Institute (KATRIN) which is responsible for rice technology improvement and transfer. The rice varieties IR64 and SARO 5 are grown in the irrigated lowlands. The yields of these varieties vary from 2.5 to 4 t ha^{-1} (IRRI, 2013). In the upland ecosystem, land races (Supa cultivars) are commonly grown. However, NERICA 1, 2, 4, 5 and 10 varieties are being introduced and the yield currently ranges from 0.8 to 1.0 t ha^{-1}. Tanzania Agricultural Research Institute (ARI-KATRIN) in collaboration with IRRI scientists developed new rice varieties IR05N 221 (locally known as Komboka) and IR03A 262 (locally known as Tai) in 2013 to boost rice production. Currently Tanzania average yield is estimated at 1.8 t ha^{-1}; the low yield is due to growing low yielding rice cultivars with long growth duration and high susceptibility to blast and bacterial leaf blight. Komboka has a yield potential of 6.5 to 7 while Tai has a yield potential of 7.5 t ha^{-1}. Komboka is desired for its aroma. Tai is non-aromatic but still preferred in many parts of Tanzania where aroma is less important. In addition, Komboka and Tai are preferred by farmers for their long, slender and translucent grains, soft texture for cooking as the texture remains soft after overnight storage compared to the popular SARO 5 (TXD 306) (IRRI, 2013).

2.15 Breeding methods in rice

2.15.1 Pure-line selection

Pure-line is the progeny of a single, homozygous, self-pollinated plant. This method involves selecting a large number of plants whose individual progenies are tested until they become uniform and stable (Arterbum et al., 2003). After ascertaining the stability of yield performance in a target environment, the best progeny is then released as a variety after evaluation for consumer quality. The process of pure-line selection begins either in farmer fields or with farmer varieties raised on experimental farms (Jennings et al., 1979). This method does not interfere with the combination of desirable characters preserved through generations of selection but the main weakness is that variability and improvement of the desired traits are both limited (Jennings et al., 1979). Mishra (2001) generated 35 rice varieties for upland and 19 for irrigated ecosystem through pure line selection. Some of the early rice varieties developed was GEB 24, Basmati 370 (traditional variety grown at the foot hills of Himalayas) and Manoharsali. These varieties had desirable genes such as *Ptb18* and *Ptb33* that confer resistance to brown plant hopper while SR 26B and Vyttila 1 for salt tolerance and FR 13A for adaptation to deep water (Singh et al., 2007).

2.15.2 Pedigree selection

This is the main selection method used in rice breeding programs (Breseghello and Coelho, 2013). Individual plants selection start with F_2 (250-500) and the progenies are tested in the subsequent segregating generations. Selection is done between and within progeny families. Data on diseases, insects and grain quality are normally scored starting from F_4 generation (Jennings et al., 1979). The harvested seeds are bulked when the progenies become homozygous and promoted to yield trials (Breseghello and Coelho, 2013). The majority of IRRI bred elite rice lines and varieties have been developed by the pedigree method.

Raboin et al., (2010) generated more than 200 crosses from local populations of temperate japonica as cold tolerance donor. These progenies were selected using pedigree method at

1500 m altitude (highlands of Madagascar). They observed that the first set of the selected varieties adapted to the cold temperatures of the high plateau and had fairly good yield potential (6 t ha^{-1}).

Sie et al., (2012) hybridized *Oryza sativa* parents with five elite high yielding japonica varieties developed by Africa Rice Centre, after two cycles of backcrossing to the respective *Oryza sativa* parents, the BC_2F_1 progenies were subjected to pedigree selection and the first fixed fertile upland interspecific progenies (WAB series) were developed.

2.15.3 Backcross method

This breeding method is normally used when simply inherited character is being transferred from a recalcitrant wild species or poor land race to an adapted variety with good agronomic traits (Mishra, 2001). In this case the F_1 generation and the progenies in the subsequent generations are repeatedly backcrossed to the donor parents used in the cross. It is advisable to go for several cycles of backcrossing of the recurrent parent with the donor variety (Arterbum et al., 2003). Backcross is an effective method for breaking tight linkages between desirable and undesirable characters and it is frequently used in rice hybrid breeding in the development of cytoplasmic male sterile lines (Mishra, 2001). Mishra (2001) used backcross breeding method to introgress bacterial leaf blight resistant genes (*Xa21* and *Xa4*) into Pusa 44 rice variety.

The overview of rice varieties generated using the above described breeding methods in several African countries are presented in Table 2.2.

Table 2.2 Rice varieties developed in Africa and their characteristics.

Country	Cultivar	Ecology	Characteristics	Year released
Benin	Cnax 3031-78-2-1 ART 3-9L6P2-B-B-1 WAB-368-B-2-H2-HB IR68702-072-1-4-B WAB-99-17 Art 3-7-L16p5-B-B-3	Upland	Drought tolerant	2013
	FKR 19	Lowland	Salinity tolerant	2009
Cote d'Ivoire	NERICA 1, 2, 3, 4, 5, 6, 7	Upland	Drought tolerant	2000
	NERICAs 8-18	Upland	Drought tolerant	2005
Burkina Faso	WAB-C-165 WAB-99-84	Upland	Drought tolerant	2013
	WAS-122-IDSA-1-WAS-6-1	Lowland	Tolerant to iron	

	WAS-20-B-B-1-2-2-2		toxicity	
	WAT-1046-B-4-3-2-2-2 IR75866-2-7-1-WAB-1	Lowland	Tolerant to iron toxicity	
	IR75884-12-12-14	Lowland		
	NERICAL-19, L-20, L-41	Lowland	Salt tolerance	2007
Gambia	IR71829-3R-28-1 IR72402-B-P-25-3-1-B	Mangrove	Tolerant to salinity	2013
Ghana	IR841	Lowland	Tolerant to iron toxicity	2013
	TOX 3737, 3233, Jasmin85	Irrigated	Salt tolerance	2009
Guinea	IR75887-1-3-WAB-1 WAT1046-B-43-2-2-2 WAT1297-B-57-1-2	Lowland	Tolerant to iron toxicity	2013
Ethiopia	IRGA370-38-1-1F-B1-1 FOFIFA-3737 WAB515-B-16A1-2	High elevation	Cold tolerant	2013
	NERICA 6, 14, 15,	Upland	Drought tolerant	2010
Kenya	IR05-N-2-2-1, NERICA 1, 4, 10, 11	Upland	Drought tolerant	2013 2007
Mali	Sahel 177, WAS 64, WAS62-B-B-14-1-4-2	Upland	Drought tolerant	2011
Mozambique	IR7708	Lowland	Tolerant to drought	2012
Sierra Leone	NERICA-L19 WAR73-1-M2-1 WAR77-3-2-2	Lowland Mangrove	Tolerant to iron toxicity Tolerant to salinity	2012
Tanzania	1R-03a-262	Lowland	Tolerant to drought	2012
	WAB56-104	Upland		2009
Uganda	ARICA5	Upland	Tolerant to drought	2013
	ARICA4, NERICA 1, NERICA 10			2007

Source: African Rice Annual Report 2014

2.16 Mating designs

These are techniques used by plant breeders to generate progenies in breeding programs and for genetic studies. There are several types of mating designs used by plant breeders and geneticists. The objective of the breeding program, time, space, cost and other biological considerations determine the choice of a mating design to be used (Nduwumuremyi, 2013).

2.16.1 Bi-parental mating design

This is the simplest mating design and is also called as paired crossing design (Mather, 1982). Large numbers of plants (n) are selected at random and hybridized in pairs to generate 1/2n full sib families (Acquaah, 2012). The progenies generated are evaluated and their variation is divided into within and between families (Hill et al., 1998). The progenies generated are either full sibs or unrelated. In this mating design, an estimate of the additive variance is obtained by comparing between and within family variance assuming no dominance and environment effects (Hill et al., 1998). Manickavelu et al., (2006) generated and evaluated bi-parental progenies for drought tolerance in rice.

2.16.2 Top cross design

Top cross is also referred to as inbred variety cross (Sleper and Poehlman, 2006). It involves crosses between a selected line and a usual parent designated as a variety, inbred line or a single cross of a known performance in open pollination (Aly et al., 2011). The opportunity to generate an improved variety is increased in top cross design and only single cross F_1's are involved in top cross because they are homozygous (Nduwumuremyi, 2013). Mosa (2010) used top cross design to assess the combining ability for new inbred lines. This method is more efficient in determining the GCA of inbred lines because it involves few crosses and simple statistical analysis. The limitation of this method is that it only estimates the GCA and not SCA (Mosa, 2010).

2.16.3 North Carolina Design I

Here, each set of genotypes designated as male is crossed to a different group of genotypes used as females (Acquaah, 2012). This design can estimate both dominance and additive variances and it can also evaluate the half and full sib families in recurrent selection procedure. However, it demands large quantity of seeds for replicated trials. It is ideal for both cross and self pollinating plants that can produce large amounts of seed and less practical for crop species that produce few amounts of seed (Nduwumuremyi, 2013).

2.16.4 North Carolina Design II

In this design, each genotype used as male is crossed to each of the females and both paternal and maternal half sibs are produced (Acquaah, 2012). It is a factorial crossing scheme and involves blocking of the mating groups so that the males and females are retained as one (Acquaah, 2012). The variation is divided into between full sib families and within full sib families and the variation between families is further divided into differences among males, females and that due to male x female interaction (Fasahat *et al.*, 2016). This design can estimate both GCA and SCA (Acquaah, 2012) but it has no provision for test of epistasis and genotype by environment interaction (Kearsey and Pooni, 1996). Mzengeza *et al.,* (2010) generated F_2 progenies by crossing NERICA varieties with Malawi rice landraces.

2.16.5 North Carolina Design III

This design involves backcrossing randomly selected F_2 plants with two inbred lines or parents from which the F_2 population was generated. Acquaah (2012) reported that North Carolina Design III was made more powerful by Kearsely and Jinks (1968) through the addition of a third tester not just the two inbred lines. The two inbred lines (parents) act as testers against which the F_2 progenies examined. Hallauer et al., (2010) reported that the F_2 population is considered a reference population for North Carolina III mating design. The triple testcross is capable of estimating additive and dominance variance as well as epistasis (Acquaah, 2012). Saleem et al., (2009) used triple test cross to study the genetic basis of seven agronomic traits in Basmati rice.

2.16.6 Diallel Mating Design

In full diallel mating design, all the parents are crossed in all possible combinations to produce hybrids and reciprocal crosses (Schlegel, 2010). The four different diallel mating schemes suggested by Griffing (1956) include; full diallel (method 1) involves parents, $F_{1's}$ and reciprocals, half diallel (method 2) includes parents and $F_{1's}$ while method 3 involves $F_{1's}$ and reciprocals and method 4 involves only the $F_{1's}$ (Fasahat et al., 2016). These diallel methods are normally used for one location trials. However, trials across multiple environments are suggested to generate authentic genetic information on the genotypes tested. Researchers such as Maurice (2010), Asfaliza et al., (2012) and Malemba et al., (2017) used method 1 to examine the gene action of different characters in rice.

2.16.7 Line x tester design

This is the most commonly used mating scheme in the development of hybrids (Fasahat et al., 2016). Here, lines are crossed with testers to generate half sib progenies, the progenies and the parents are assessed in field trials (Sharma, 2006). It can also estimate the SCA of each cross as well as the GCA of lines and testers since the lines and the testers are considered different sets of genotypes (Sharma, 2006). Saleem et al., (2010), Sathya and Jebaraj (2015) used line x tester design to conduct genetic studies in hybrid rice.

CHAPTER THREE

COMBINING ABILITY AND HETEROSIS FOR AGRONOMIC AND YIELD TRAITS IN INDICA AND JAPONICA RICE CROSSES

3.0 ABSTRACT

Breeding rice for yield potential and grain quality requires careful selection of the parental genotypes that possess high yield potential and with good cooking and eating characteristics. Rice in eastern Africa is predominantly grown by smallholder farmers with an estimated yield of about 1,800 kg ha^{-1}. The understanding of genetic variability and mode of gene action for agronomic and yield traits are important in formulation of effective rice breeding program for genetic enhancement of grain yield. The objective of this study was to determine the combining ability and heterosis for agronomic and yield traits in indica and japonica rice crosses.

Twenty seven F$_1$ hybrids were generated from crosses between nine male indica parents (NERICA 1, SARO 5, 08 FAN 10, *Dourado precoce*, PAN 84, Komboka, IR 27-93-80-1-4 and Basmati 217 and Basmati 370) and three japonica females (K$_2$-8, K$_2$-9 and K$_2$-54) using North Carolina Design II mating system. The 27 F$_1$ hybrids and their 12 parents were evaluated at Mwea Research Station during the cropping season of 2017. Data was collected on agronomic and yield traits and subjected to analysis of genetic designs in R (AGD-R) version 3.0.

The results showed that general combining ability (GCA) was significant ($P \leq 0.05$) for days to 50 % flowering, days to maturity, number of tillers plant^{-1}, number of spikelet's panicle^{-1}, number of effective tillers plant^{-1}, number of fertile grains panicle^{-1}, and grain yield indicating the dominance of additive gene action in the expression of these traits. Specific combining ability (SCA) was significant ($P \leq 0.05$) for plant height, panicle length, flag leaf length and 1000 grain mass suggesting the dominance of non-additive gene action in the control of these traits. Basmati 370, Basmati 217, K$_2$-54 and Komboka were best general combiners for grain yield. Hybrids K$_2$-9 x Komboka, K$_2$-9 x Basmati 370, K$_2$-54 x *Dourado Precoce* and K$_2$-54 x Basmati 217 were good specific combiners for grain yield. The best specific combiners originated from high x high GCA combinations and could be attributed to additive x additive type of gene actions thus the yield potential of these crosses can be fixed in subsequent generations and produce desirable transgressive segregants which can be recognized by pedigree breeding method. However, high SCA effects of hybrids from high x low GCA combining parents would be unfixable in subsequent generations and thus requires modification of the breeding method to accommodate both additive and non-additive genetic effects in order to fix the yield potential of these crosses in later generations.

The results of heterosis showed significant variation for agronomic and yield characters in all 27 F_1 hybrids studied. Heterosis for grain yield was observed in the hybrids K_2-9 x Basmati 370 (31 %), K_2-9 x Komboka (24 %), K_2-8 x Basmati 217 (23 %), K_2-54 x Basmati 217 (21 %), K_2-54 x *Dourado precoce* (20 %) and K_2-8 x Basmati 370 (18 %). Heterosis for number of tillers plant^{-1}, panicle length, number of panicles plant^{-1} and filled grains panicle^{-1} was observed in the F_1 hybrids. Negative heterosis for earliness was observed in the hybrids K_2-54 x Basmati 370 (-8 %) and K_2-54 x *Dourado precoce* (-4 %). Thus, the hybrids K_2-9 x Basmati 370, K_2-8 x Basmati 217, K_2-54 x Basmati 217 and K_2-9 x Komboka exceeded the yield level of the standard check variety (Basmati 370) by 20 % implying that they have high yield potential that could be exploited for hybrid rice production. The high yielding parental genotypes are recommended as donors in rice breeding program while the F_1 hybrids could be advanced to F_6 or F_7 to ascertain their yield potential and further evaluated in a wide range of environments.

Key words: Combining ability, earliness, gene action, grain yield, heterosis, *Oryza sativa*

3.1 INTRODUCTION

Rice is the second most important food crop globally after maize and provides over 20 % of the daily calorie intake for 3.9 billion people globally (Kohnaki et al., 2013).

Annual rice production in Africa was estimated at 31 million t from 11 million hectares under cultivation (FAO, 2017).

Rice forms a larger part of the diet for both urban and rural populations in Kenya. Kenya produces about 140,000 metric tonnes against a demand of over 540,000 metric tonnes per year (MoA, 2014). Unfortunately, rice yield per hectare is low (< 3.6 t ha^{-1}) because smallholder farmers rely on local cultivars with low yield potential, highly susceptible to bacterial leaf blight and rice blast (Kimani, 2010). Small holder farmers at Mwea irrigation scheme mainly grow Basmati rice under irrigated ecosystem. Basmati rice is mainly preferred by most consumers due to its aroma and good cooking qualities (Njiruh *et al.,* 2013). However, Basmati yield per hectare is low (3.0 t ha^{-1}) and upland rice varieties are marginally practiced despite their enormous potential in increasing national production (Kimani, 2010). This stagnation in productivity led to decline in consumption of locally produced rice and increased imports from Pakistan, China, India and Vietnam (MoA, 2014).

Breeding upland rice for grain yield requires an understanding of the gene action of agronomic and yield traits as a prerequisite for improving the yield potential of the local rice cultivars (Dar *et al.,* 2014). Various biometrical techniques have been used to analyze genetic variability for yield traits (Comstock and Robinson, 1948; Griffing, 1956; Kempthrone, 1957; Kempthrone and Curnow, 1961). Combining ability analysis provides information on the nature and magnitude of gene effects that regulate grain yield and yield traits enabling the breeder to design an effective breeding program for genetic enhancement of grain yield and yield components (Dar et al., 2014).

Heterosis is expressed in three ways depending on the criteria used to compare the performance of the hybrid (Alam et al., 2004). These three ways are mid-parent heterosis, better parent heterosis and standard heterosis.

From a practical point of view, standard heterosis is more important of the two levels of heterosis because it is aimed at developing desirable hybrids superior to the existing high yielding commercial varieties (Chaudhary, 1984). This study was carried out to determine the combining ability and heterosis for agronomic and yield traits in indica and japonica crosses as a criterion for developing superior rice varieties.

3.2 MATERIALS AND METHODS

3.2.1 Study location

The experiment was conducted in an upland rainfed ecosystem during the long rain season between April and September 2017 at Mwea Research Station. It is one of the research stations of the Industrial Crops Research Institute of Kenya Agricultural and Livestock Research Organization (KALRO). It is located in Mwea Division, Kirinyaga South District, Kirinyaga County, Kenya. The research station is located 24 km south-west of Embu town, and approximately 112 km north east of Nairobi (KARI, 2000). Mwea Research Station lies on a latitude 0 37’S and Longitude 37 20’E at an elevation of 1159 m above sea level. The soil type is a nitosol with a pH of about 5.65.

3.2.2 Germplasm

The male parents used in this study were indica type while the female parents were japonica type of rice (Table 3.1). The germplasm used were obtained from the Industrial Crops Research Centre (ICRC) - Mwea. The parental genotypes were chosen based on yield potential, resistance to both biotic and abiotic stresses and high grain quality attributes. The pedigree and origin of the 12 parents are presented in Table 3.1.

Table 3.1 Characteristics of parents used in the crossing block.

S/N	Pedigree	§Source	Primary selection criteria	Reference
G1	NERICA 1	ARC	Aroma, high grain quality, earliness, drought and blast resistant and high yield (5.1 t ha-^{1})	WARDA, 2008
G2	SARO 5	ARI-KATRIN	Semi aromatic, high yielding (8-10 t ha^{-1}), earliness, high tillering (30-50 tillers)	ARI, 2011
G3	08 FAN 10	ARC	Semi aromatic, earliness, resistant to blast and high grain quality	WARDA, 2008
G4	Basmati 370	IRRI	Aroma, high grain quality, high yield (5.3 t ha^{-1}), resistant to rice yellow mottle virue (RYMV) and well adapted to lowlands	IRRI, 2012
G5	Basmati 217	IRRI	Aroma, high grain quality high yield (4.6 t ha^{-1}), resistant to RYMV and adapted to low nitrogen	IRRI, 2000
G6	*Dourado precoce*	Kenya cultivar from Brazil	Moderate yielding (4.1 t ha^{-1}), good cooking, high grain quality and adapted to highlands	KALRO, 2007
G7	PAN 84	KALRO-ICRC, Mwea	High yielding (6.5 t ha^{-1}), good grain quality, tolerant to blast and well adapted to upland and lowland areas	KALRO, 2008
G8	IR 27-93-80-1-4	IRRI	High yielding (7.6 t ha^{-1}), earliness and good grain quality	IRRI, 2008
G9	Komboka	IRRI	High yielding (8.6 t ha^{-1}), good grain quality, tolerant to blast and well adapted to upland and lowland areas	ARI, 2002

G10	K2-9	RDA-KAFACI Korea	High yielding (5.4 t ha^{-1}), earliness and well adapted to irrigated lowlands upland areas	KALRO, 2014
G11	K2- 8	RDA-KAFACI Korea	High yielding (6.7 t ha^{-1}), earliness and well adapted to irrigated lowlands upland areas	KALRO, 2012
G12	K2- 54	RDA-KAFACI Korea	High yielding (7.6 t ha^{-1}), earliness and well adapted to irrigated lowlands upland areas	KALRO, 2013

§ ARC - Africa Rice Centre, ARI-KATRIN- Agricultural Research Institute - Kilombero Agricultural Research and Training Institute, IRRI - International Rice Research Institute. G1 to G12: Code used for 12 parents in the crossing block, WARDA - West African Rice Development Association, KAFACI - Korea-Africa Food and Agriculture Cooperation Initiative.

3.2.3 Planting the study materials

The parental cultivars were planted in buckets (29.9 cm in diameter, 54.9 cm in height and a volume of 32162.5 cm^3) and grown in a greenhouse conditions. The seeds were sown using the direct seeding method with two seeds per hill. The cultivars were replicated three times at an interval of 1, 14 and 21 days to synchronize flowering and facilitate generation of enough F_1 seeds. Di-ammonium phosphate fertilizer was applied at a rate of 50 kg N ha^{-1} and 40 kg P ha^{-1} during planting in order to enhance plant and root vigour.

3.2.4 Development of F_1 hybrids

The nine male indica and three female japonica parents were grown in a hybridization nursery of about 5 m^2 x 5 m^2 at Industrial Crops Research Centre between March and June 2016. The cultivars were crossed using North Carolina II mating design (Comstock and Robinson, 1952). These crosses generated 27 F_1 hybrids.

North Carolina Mating Design II

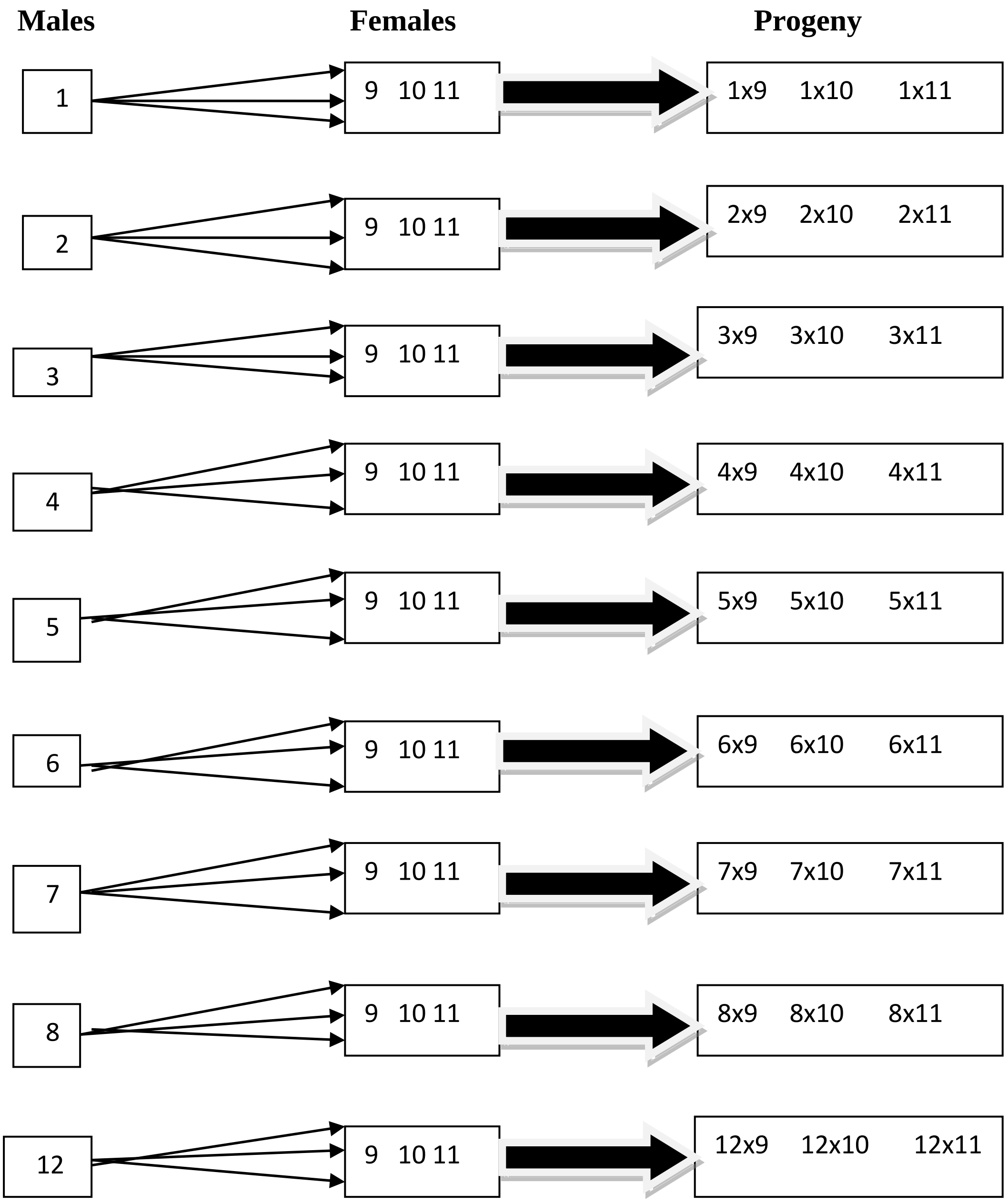


Figure 3.0 North Carolina Design II Mating scheme; where 1 = NERICA 1, 2 = SARO 5, 3 = 08FAN 10, 4 = Basmati 370, 5 = Basmati 217, 7 = Dourado precoce, 6 = PAN 84, 12 = IR2729-80-1-4, 8= Komboka, 9 = K$_2$-9, 10 = K$_2$8, 11 = K$_2$54.

3.2.5 Preparation of female parent

The cultivars were ready for emasculation when 50 to 60 % of the panicle emerged from the boot. The flag leaf of the panicle to be emasculated was bent carefully to avoid breaking the stem. Scissors were used to cut off all florets that had already reached anthesis.

Young and immature florets also were cut off from the bottom as well as those at the tip of the panicle. One third to one half of the tissue of the remaining florets were cut away to expose the anthers. The six anthers were removed by using forceps or a vacuum emasculator set at a pressure of 15 kPa. The emasculated panicles were covered with a glassine bag to avoid contamination from unwanted pollen. The glassine bag was closed by folding the open edge diagonally and fastening it with a paper clip (Coffman and Herrera, 1980).

Figure 3.1 Ready pollen for pollination **Figure 3.2 Cutting half the young floret with scissors**

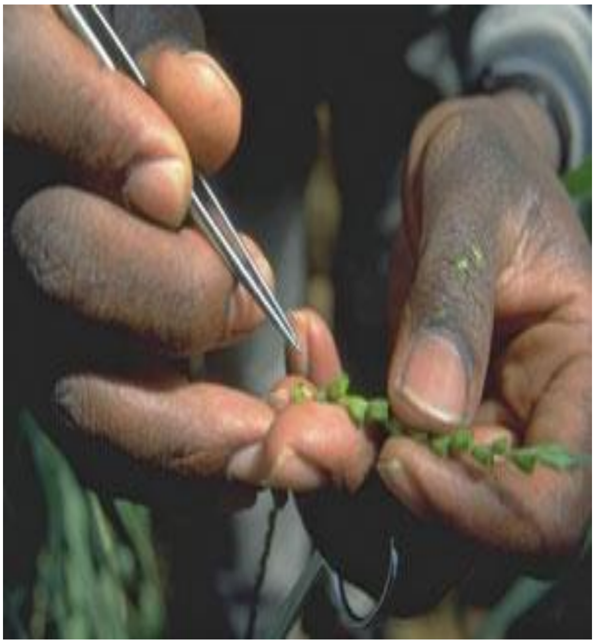


Figure 3.3 Removal of the anthers using forceps **Figure 3.4 Covering of emasculated panicles**

3.2.6 Pollination

The panicles of the male parents were cut using scissors before anther dehiscence and taken to the location of the female parents. The glassine bag was removed from the emasculated female parent and the pollinator panicles were gently shaken over the female panicle. The glassine bag was replaced over the female parent and the details of the male and female parents, emasculator and date of pollination were recorded on the tag, and attached to the female panicle (Coffman and Herrera, 1980).

Figure 3.5 Dusting of the stigma using forceps

Figure 3.6 Preparing, dusting and covering the panicles

3.2.7 Harvesting of the F_1 seed

The F_1 seeds lost their green colour at about 25 days after pollination and were considered mature; the seeds from each female were harvested, threshed and bagged separately. Details of the cross including date of harvesting and the number of seeds were recorded on the bag. The F_1 seeds were sun dried and stored in khaki envelops (Fig 3.1).

Figure 3.7 Bags for storing F_1 seeds

3.2.8 Evaluation of F_1 progeny

The 27 F_1 hybrids and their 12 parents were evaluated at Mwea Research Station during the long rain season between March and July 2017. The trial was laid out in a randomized complete block design with three replications. The seeds were sown by direct seeding with an inter-row spacing of 20 cm and intra-row spacing of 20 cm with two seeds per hill. When the seedlings were 2-3 weeks old, gapping and thinning was carried out leaving one seedling per hill to ensure uniform plant density. Hand weeding was carried out at an interval of 20, 40 and 60 days after planting. DAP fertilizer (18:46:0) was applied during planting at a rate of 50 kg N ha^{-1} and 40 kg P ha^{-1}. First top dressing was carried out at active tillering using NPK (17:17:17) fertilizer applied at a rate of 120 kg N ha^{-1}, 30 kg P ha^{-1} and 90 kg K ha^{-1}. Calcium ammonium nitrates (CAN) fertilizer was applied at panicle initiation stage at a rate of 100 kg N ha^{-1}. The trial was irrigated twice every week while pesticide (Duduthrin 1.75 EC, Lambda-cyhalothrin 17.5 g/L) was applied every two weeks at a rate of 50 ml/20L of water to control stem borer, fall armyworm and leaf hoppers.

3.3 DATA COLLECTION

Data for agronomic and yield traits were collected according to the procedure outlined in Standard Evaluation System (SES) for rice (IRRI, 2013). The quantitative and qualitative data was collected at appropriate stages of crop development namely at the vegetative, flowering, maturity and harvesting stage.

i. Days to 50 % flowering: were recorded as the duration from sowing to when half of the plants in a plot and half of the tillers in these plants had flowered.
ii. Plant height: The height of the plant from the plant base to the tip of the highest panicle excluding the awn was measured using a ruler.
iii. Number of tillers $plant^{-1}$: The numbers of tillers $hill^{-1}$ were determined by counting and recording all emerging shoots.
iv. Days to maturity: The duration from time of seedling emergence up to the day when 85 % of the spikelets were mature was recorded.
v. Flag leaf length: The leaf immediately beneath the spike was measured from the collar to the nodal end of the leaf using a meter ruler.

vi. Panicle length: The length of the panicle was measured from the neck node base to the tip of the top most grain in the panicle using a meter ruler.

vii. Number of fertile tillers plant^{-1}: This was recorded as the numbers of tillers bearing panicles at physiological maturity.

viii. Number of spikelet's panicle^{-1}: The numbers of spikelets on each panicle were counted.

ix. Number of filled grains panicle^{-1}: Two plants were sampled per pot and the panicles harvested, threshed and dried to 14 % moisture level. The filled and the unfilled grains were separated using the floatation method (IRRI, 2013). The grains which sunk to the bottom of the beaker and those that floated were dried separately and the total number of the filled (sunk) and unfilled grains (floated) were counted and recorded. The samples were replicated three times in order to minimize errors.

x. Grain yield plant^{-1}: The mature panicles were harvested, threshed, cleaned and dried to 12-14 % moisture level. The threshed grains per plant were weighed using electronic weigh balance (model SP 401, OHAUS Lab balances, Amazon UK) and recorded in grams and converted to kg ha^{-1}. The grain yield plot^{-1} was calculated using the formula described by Gomez (1972). Grain yield = $\frac{\boldsymbol{W}}{\boldsymbol{n}} \boldsymbol{x} \boldsymbol{N}$...Equation 1

Where; w= weight of the grain from the harvested hills

n= number of harvested hills

N= total number of hills in a plot

xi. Thousand seed mass: 1000 grains from each of the harvested plants were counted using electronic grain counter (model AG64-100, Wagtech International, New York) and weighed by electronic weighing balance (model SP 401, OHAUS Lab balances, Amazon UK) after drying the grains to moisture content of 14 %.

Figure 3.8 Electronic grain counter and weighing balance

3.4 DATA ANALYSIS

The data was subjected to analysis of variance with genotype as the fixed factor using analysis of genetic designs in R (AGD-R) version 3.0 (Gregorio et al., 2015). Their means were separated using the least significant differences (LSD) at $P \leq 0.05$.

3.4.1 Estimates of combining ability

The combining ability analysis was carried out as per the method suggested by Comstock and Robinson (1948) using Analysis of Genetic designs in R (AGD-R) version 3.0 (Gregorio et al., 2015). In North Carolina mating design II, the variation between families is further divided into component differences among males, females and that due to male x female interaction following the statistical model suggested by Comstock and Robinson (1952).

The statistical model used was: $Y_{ijk} = \mu + M_1 + F_j + (M \times F)_{ij} + e_{ijk}$.........................Equation 2

Where; $\mathbf{Y_{ijk}}$ = is the Kth observation on i x jth progeny

M= is the general mean

$\mathbf{M_1}$= is the effect of the ith male

$\mathbf{F_j}$= is the effect of the jth female

$\mathbf{(M \times F)_{ij}}$= is the interaction effect

$\mathbf{e_{ijk}}$= is the error associated with each observation

The expectations of males and females in this design were equivalent to the general combining ability (GCA) and the interaction between males and females were equivalent to the specific combining ability (SCA).

F-tests were done to examine the differences between males and females. The estimates of the GCA and the SCA effects for the parents and their progenies were calculated based on the statistical model by Comstock and Robinson (1952).

GCA effect (g_1) = $\frac{(\mathbf{Msm - Msmxf})}{Fr - Cov(Hs)}$ = ¼ σ^2A..Equation 3

GCA effect (g_2) = $\frac{(\mathbf{Msf - Msmxf})}{Mr - Cov(Hs)}$ = ¼ σ^2A..Equation 4

SCA effect (s_1) = $\frac{(\mathbf{Msmxf - Mse})}{r - Cov(Fs) - 2Cov(Hs)}$ = ¼ σ^2D...Equation 5

3.4.2 Partitioning of variance components

The ratio of the combining ability variance components examine the type of gene action involved in the expression of traits hence allowing optimum allocation of resources in hybrid breeding (Fasahat et al., 2016). The ratio of GCA and SCA was computed according to Baker (1978)

$\frac{2\sigma^2 gca}{2\sigma^2 gca - \sigma^2 sca}$ … . . … … …..Equation 6

Where; σ^2gca denotes general combining ability variance and σ^2sca for specific combining ability variance. A ratio closer to one reveals GCA action while a ratio of less than one predicts SCA action.

3.4.3 Estimation of heterosis

The magnitude of heterosis in the F_1 hybrids was calculated in relation to the better parent rice variety as percent increase or decrease of the F_1 hybrids over the better parent. Better parent heterosis was computed according to Virmani et al., (1997).

$\frac{\mathbf{F_1 - BP}}{\mathbf{BP}} \times \mathbf{100}\ \%$ … … … … … … … … . …...Equation 7

Where: F_1= mean performance of a single cross and BP= mean performance of the better parent.

3.5 RESULTS

3.5.1 Duration to 50 % flowering

The analysis of variance showed highly significant genotypic differences ($P \leq 0.001$) for days to 50 % flowering (790.3***) among the genotypes (Table 3.2). The analysis of variance for combining ability showed a highly significant differences ($P \leq 0.001$) among the male (1127.0**) and female parents (90.8**) for duration to 50 % flowering. There were highly significant differences ($P \leq 0.001$) due to male x female interaction effects (Table 3.3). Duration to 50 % flowering varied between 82.0 to 118.3 d among the parents while the same traits ranged from 59.7 to 127.0 d among the hybrids (Table 3.4). A higher success rate of 81.8 % was observed in the cross K_2-54 x Basmati 370 for days to 50 % flowering (Table 3.5). A cross between a moderately flowering (87 d) japonica parent (K_2-54) and an indica parent (Basmati 370) with longer duration to 50 % flowering (100 d) led to the generation of early flowering F_1 hybrid (K_2-54 x Basmati 370) with 59.7 d to flowering. K_2-54 exhibited complete dominance over the late maturing parent. Photoperiod sensitivity affected flowering and generation of the crosses.

3.5.2 85% Days to maturity

The analysis of variance showed highly significant genotypic differences ($P \leq 0.001$) for days to maturity (390.1***) among the genotypes studied (Table 3.2). Combining ability for days to maturity was highly significant ($P \leq 0.001$) among the male (668.7**) and female parents (194.8**) (Table 3.3). Days to maturity varied between 112 to 157 days among the parental lines with IR-27-93-80-1 (157 d) followed by Basmati 370 (142 d) taking the longest time to maturity while $K_{2\text{-}}8$ (112 d) took the least days to maturity. Duration to maturity varied between 109 to 149 days among the F_1 hybrids with $K_{2\text{-}}54$ x Basmati 217 (149 d) taking the longest time to maturity while $K_{2\text{-}}54$ x *Dourado precoce* (109 days) took the shortest time to maturity (Table 3.4). Some of the parental lines were photoperiod sensitive and it affected the duration to maturity among the parents. A higher success rate of 72.7 % was observed in the cross K_2-54 x *Dourado precoce* for days to maturity (Table 3.5). A cross between medium maturing japonica ($K_{2\text{-}}54$) parent and late maturing indica parent (*Dourado precoce*) led to the development of an early maturing F_1 hybrid $K_{2\text{-}}54$ x *Dourado precoce* (109 d). The parent K_2-54 exhibited partial dominance over the late maturing parent.

3.5.3 Plant height

The analysis of variance showed highly significant genotypic differences ($P \leq 0.001$) for plant height (1247.9***) among the genotypes (Table 3.2). Analysis of combining ability was highly significant ($P \leq 0.001$) for plant height among the male (2805.8**) and female parents (98.3**). The means squares due to male x female interaction effects were highly significant ($P \leq 0.001$) (Table 3.3). Plant height varied from 78.3 to 139.3 cm among the parents. The parent *Dourado precoce* (139.3 cm) exhibited the tallest plants while IR-27-93-80-1 (78.3 cm) had the shortest plants. Among the F_1 hybrids, plant height varied between 71.3 to 155.0 cm with K_2-8 x Komboka (71.3 cm) followed by K_2-54 x Komboka (75 cm) and K_2-9 x IR-27-93-80-1 (76.3 cm) exhibiting the shortest plants while K_2-54 x Basmati 370 (155 cm) and K_2-54 x Basmati 217 (135 cm) had the tallest plants (Table 3.4). A lower success rate (27.7 %) was observed in the cross K_2-8 x Komboka for plant height (Table 3.5). A cross between indica (Komboka) and japonica parent (K_2-8) both with intermediate heights of 91 and 95 cm respectively led to generation of a short F_1 hybrid (K_2-8 x Komboka). Additive gene action was dominant in the inheritance of this trait in the F_1 progeny.

3.5.4 Number of tillers per plant

The analysis of variance showed highly significant genotypic differences ($P \leq 0.001$) for number of tillers (585.8***) among the genotypes (Table 3.2). Number of tillers per plant was highly significant ($P \leq 0.001$) among the male (1000.4**) and female parents (149.9**) (Table 3.3). Number of tillers ranged from 16 to 62 among the parents with Basmati 217 (62) exhibiting the highest number of tillers per plant while PAN 84 (16) had the lowest tillers. Among the F_1 hybrids, tiller numbers varied from 30 to 88 with K_2-9 x Komboka (88) followed by K_2-54 x Basmati 370 (77) and K_2-54 x Basmati 217 (70) exhibiting the highest number of tillers per plant while K_2-54 x PAN 84 (30) had the lowest tillers (Table 3.4). A higher success rate (90.9 %) was observed in the cross K_2-9 x Komboka for number of tillers per plant (Table 3.5). A cross between a high tillering parent K_2-9 (55) and Komboka (50) led to development of an F_1 hybrid, K_2-9 x Komboka with high number of tillers per plant (88). Additive gene action was dominant in the inheritance of this trait in the F_1 progeny.

3.5.5 Flag leaf length

The analysis of variance showed highly significant genotypic differences (P≤0.001) for flag leaf length (126.3***) among the genotypes (Table 3.2). Combining ability analysis for flag leaf length was highly significant (P≤0.001) among the male (183.2**) and female parents (82.2**). Male x female interaction was highly significant (P≤0.001) for flag leaf length (Table 3.3). Flag leaf varied from 20 to 44 cm among the parents with Basmati 370 exhibiting the longest flag leaf while SARO 5 (20 cm) had the shortest flag leaf. Flag leaf ranged from 20 to 47.3 cm among the F_1 hybrids with K_{2}-54 x Basmati 217 (47.3 cm) followed by K_{2}-9 x PAN 84 (42.3 cm) exhibiting the longest flag leaf while K_{2}-8 x SARO 5 (20 cm) had the shortest flag leaf (Table 3.4). A lower success rate (16.2 %) was observed in the cross K_{2}-54 x Basmati 217 for flag leaf length (Table 3.5). A cross between japonica parent (K_{2}-54) with medium flag leaf and indica parent (Basmati 217) with long flag leaf led to the generation of an F_1 hybrid, K_{2}-54 x Basmati 217 with longest flag leaf (47.3 cm). Additive gene action was dominant in the inheritance of this trait in the F_1 progeny.

3.5.6 Panicle length

The analysis of variance showed highly significant genotypic differences (P≤0.001) for panicle length (24.19***) among the genotypes (Table 3.2). Combining ability showed highly significant differences (P≤0.001) for panicle length among the male (51.5**) while non-significant differences were observed among the female japonica parents (0.8**). Male x female interaction was highly significant (P≤0.001) for panicle length (Table 3.3). Panicle length varied between 18 to 29 cm among the parents with Basmati 217 (29 cm) followed by Basmati 370 (28 cm) exhibiting the longest panicle while 08FAN 10 (18 cm) had the shortest panicle. Among the F_1 hybrids, panicle length varied between 18 to 30 cm with K_{2}-54 x Basmati 217 (30 cm) exhibiting the longest panicle while K_{2}-9 x 08FAN 10 (18 cm) had the shortest panicle (Table 3.4). A lower success rate (16.2 %) was observed in the cross K_{2}-54 x Basmati 217 for panicle length (Table 3.5). A cross between K_{2}-54 japonica with short panicle (21 cm) and indica parent Basmati 217 (29 cm) led to the generation of an F_1 hybrid, K_{2}-54 x Basmati 217 with longer panicle (30 cm). The parent Basmati 217 exhibited complete dominance in the expression of this trait in the F_1 progeny.

3.5.7 Number of panicles per plant

The analysis of variance showed highly significant genotypic differences ($P \leq 0.001$) for number of panicles per plant (352.5***) among the genotypes studied (Table 3.2). Combining ability analysis showed highly significant difference ($P \leq 0.001$) for number of panicles among the male (520.78**) and female parents (78.37**) (Table 3.3). The number of panicles varied from 15 to 53 among the parental lines with Basmati 217 (53) exhibiting the highest number of panicles per plant while PAN 84 (15) had the least number of panicles. Among the F_1 hybrids, the number of panicles ranged from 24.67 to 74.33 with K_2-9 x Komboka (74.33) followed by K_2-54 x Basmati 217 (60) exhibiting the highest number of panicles per plant while the hybrid K_2-54 x *Dourado precoce* (24.67) had the least number of panicles (Table 3.4). A higher success rate (90.9 %) was observed in the cross K_2-9 x Komboka for number of panicles per plant (Table 3.5). A cross between japonica (K_2-9) with high number of panicles and indica parent (Komboka) with moderate number of panicles (34) led to development of an F_1 hybrid, K_2-9 x Komboka with the highest number of panicles per plant (74). Additive gene action was dominant in the inheritance of this trait in the F_1 progeny.

3.5.8 Number of spikelets per panicle

The analysis of variance showed highly significant genotypic differences ($P \leq 0.001$) for number of spikelets per panicle (8.89***) among the genotypes studied (Table 3.2). Combining ability analysis showed highly significant differences ($P \leq 0.001$) for number of spikelets per panicle among the male (19.9**) and female parents (2.7**) (Table 3.3). The number of spikelets ranged from 10.1 to 15 among the parents with SARO 5 (15) exhibiting the highest number of spikelets while K_2-9 (10.1) had the lowest spikelets per panicle. Among the F_1 hybrids, the number of spikelets ranged from 9.7 to 16.0 with K_2-8 x SARO 5 (16) followed by K_2-54 x Komboka (15) exhibiting the highest number of spikelets per panicle while K_2-8 x NERICA 1 (9.7) had the lowest number of spikelets (Table 3.4). A high success rate (72.7 %) was observed in the cross K_2-8 x SARO 5 for number of spikelets per panicle (Table 3.5). A cross between japonica (K_2-8) with low number of spikelets (10) and indica parent (SARO 5) with high number of spikelets (15) led to the generation of an F_1 hybrid, K_2-8 x SARO 5 with highest number of spikelets per plant (16). A higher success rate was observed in this cross. The parent SARO 5 exhibited complete dominance in the expression of this trait in the F_1 progeny.

3.5.9 Filled grains per panicle

The analysis of variance showed highly significant genotypic differences ($P \leq 0.001$) for filled grains per panicle (1034.4***) among the genotypes (Table 3.2). Combining ability analysis for filled grains per panicle was highly significant ($P \leq 0.001$) among the male (1379.8**) and female parents (1068.4**) (Table 3.3). Filled grains per panicle ranged from 91 to 148 among the parents with Basmati 370 (148) followed by *Dourado precoce* (129.67) exhibiting the highest number of filled grains per panicle while K_2-9 (91) had the lowest filled grains. Among the F_1 hybrids, filled grains ranged from 81 to 150 with K_2-9 x Komboka (150) followed by K_2-54 x SARO 5 (144) exhibiting the highest number of filled grains per panicle while K_2-54 x *Dourado precoce* (81) had the lowest filled grains (Table 3.4). A higher success rate (90.9 %) was observed in the cross K_2-9 x Komboka for number of filled grains per panicle (Table 3.5). A cross between japonica parent (K_2-9) with low number of filled grains (91) and indica parent (Komboka) with high number of filled grains (115) led to the generation of an F_1 hybrid, K_2-9 x Komboka with highest number of filled grains per panicle (150). The parent Komboka exhibited complete dominance in the inheritance of this trait in the F_1 progeny.

3.5.10 Grain yield

The analysis of variance showed highly significant genotypic differences ($P \leq 0.001$) for grain yield (3647150***) among the genotypes (Table 3.2). Combining ability analysis showed highly significant differences ($P \leq 0.001$) for grain yield among the male (686**) and female parents (630**) (Table 3.3). Grain yield varied from 3,157 to 5,470 kg ha^{-1} among the parents with Basmati 217 (5,877 kg ha^{-1}) followed by PAN 84 (4,967 kg ha^{-1}) exhibiting the highest grain yield while IR-27-93-80-1 (3,157 kg ha^{-1}) had the lowest grain yield. Among the F_1 hybrids, grain yield ranged from 3,370 to 6,843 kg ha^{-1} with K_2-54 x Basmati 217 (6,843 kg ha^{-1}) followed by K_2-8 x Basmati 370 (6,803 kg ha^{-1}) and K_2-54 x *Dourado precoce* (6,120 kg ha^{-1}) exhibiting the highest grain yield while K_2-9 x NERICA 1 (3,370 kg ha^{-1}) was the least grain yielder (Table 3.4). A lower success rate (16.2 %) was observed in the cross K_2-54 x Basmati 217 for grain yield (Table 3.5). A cross between a high yielder indica (Basmati 217) and japonica parent (K_2-54) a moderate grain yielder (4,317 kg ha^{-1}) gave rise to a high yielding F_1 hybrid, K_2-54 x Basmati 217 (6,843 kg ha$^{-1)}$. Additive gene action was dominant in the inheritance of this trait in the F_1 progeny.

3.5.11 1000-grain mass

The analysis of variance showed highly significant genotypic differences ($P \leq 0.001$) for 1000-grain mass (790.3***) among the genotypes studied (Table 3.2). Combining ability showed significant differences ($P \leq 0.05$) among the male (5.4**) and female parents (0.8*) for 1000 seed mass. Male x female interaction was highly significant ($P \leq 0.001$) for 1000 seed mass (Table 3.3). Among the parental lines, 1000 seed mass ranged from 23.6 to 27.9 g with PAN 84 (27.9 g) followed by *Dourado precoce* (27.2 g) exhibiting the heaviest grains while K_{2}-9 (23.6 g) had the lightest grain mass. Among the F_1 hybrids, 1000 seed mass ranged from 23.0 to 27.2 g with K_{2}-54 x PAN 84 (27.2 g) followed by K_{2}-9 x *Dourado precoce* (27.2 g) exhibiting the heaviest grains while K_{2}-54 x 08FAN 10 (23.0 g) had the lightest grains (Table 3.4). A moderate success rate (45.5 %) was observed in the cross K_{2}-54 x PAN 84 for 1000-seed mass (Table 3.5). A cross between a japonica parent (K_{2}-54) with light grains (23.21 g) and an indica parent (PAN 84) with heavy grains (27.93 g) led to the generation of an F_1 hybrid, K_{2}-54 x PAN 84 with heavy 1000 seed mass (27.2 g). The male parent PAN 84 exhibited complete dominance in the expression of this trait in the F_1 progeny.

Table 3.2 Analysis of variance (ANOVA) for different agronomic and yield traits.

		Mean squares										
Source of variation	D.f	**50% Days to flowering**	**Days to maturity**	**Plant height (cm)**	**Panicle length (cm)**	**Flag leaf length (cm)**	**Number of tillers plant^{-1}**	**Number of spikelets panicle^{-1}**	**Number of panicles plant^{-1}**	**Filled grains panicle^{-1}**	**Grain yield (kg ha^{-1})**	**1000 grain weight (g)**
Replication	2	16.38	8.78	0.70	0.31	0.64	3.49	0.60	4.93	152.94	437137	0.05
Genotype	26	790.3***	390.1***	1247.9***	24.19***	126.3***	585.82***	8.89***	352.5***	1034.4***	3647150***	4.46***
Residual	52	5.99	7.80	1.54	0.42	1.10	8.93	0.32	9.48	18.36	96291	0.18

Table 3.3 Analysis of variance for combining ability of 12 rice parental lines and their F_1 progeny for agronomic and yield traits.

		Mean squares										
Source of variance	**D.f**	**50% Days to flowering**	**Days to maturity**	**Plant height (cm)**	**Panicle length (cm)**	**Flag leaf length (cm)**	**Number of tillers plant^{-1}**	**Number of spikelets panicle^{-1}**	**Number of panicles plant^{-1}**	**Number of filled grains panicle^{-1}**	**Grain yield (kg ha^{-1})**	**1000 grain weight (g)**
Replication	2	15.3	8.8	0.7	0.3	0.6	3.5	0.6	4.9	152.9	440	0.1
Male (GCA)	8	1127.0**	668.7**	2805.8**	51.5**	183.2**	1000.4**	19.9**	520.8**	1379.8**	686**	5.4**
Female (GCA)	2	90.8**	194.8**	98.3**	0.8	82.2**	149.9**	2.7**	78.4**	1068.4**	630**	0.8*
M x F (SCA)	16	574.9**	275.1**	612.6**	13.5**	103.3**	433.0**	4.1**	302.7**	857.4**	242**	4.4**
Error	52	12.8	7.8	1.5	0.4	1.1	8.9	0.3	9.5	18.4	100	0.2
σ^2m	-	67.32	44.72	243.68	4.23	8.88	66.53	1.78	27	58.05	0.52	0.15
σ^2f	-	7.72E-13	0	0	0	0	1.28E-14	1.99E-15	0	7.81	0	0
σ^2m x f	-	169.47	86.14	203.7	4.34	34.07	130.88	1.21	89.43	279.67	0.71	1.28
σ^2A	-	926.44	509.68	524.33	8.86	18.95	769.18	11.43	457.43	1354.66	4.73	5.14
σ^2D	-	677.88	344.54	814.8	17.36	136.27	523.52	4.85	357.73	1118.7	2.83	5.74
σ^2A/ σ^2D	-	1.4	1.5	0.6	0.5	0.1	1.5	1.35	1.27	1.21	1.67	0.89

D.f= Degrees of freedom, * Significance at 5 % level of probability, ** Significance at 1 % level of probability, σ^2m= Male variance, σ^2f= Female variance, σ^2m x f= Interaction effect of male and female, σ^2A= Additive variance, σ^2D= Dominance variance

Table 3.4 Mean performance of parental lines and their crosses for different yield traits at Mwea Research Station.

	Agronomic traits								Yield traits		
Parents and crosses	**50% Days to flowering**	**Days to maturity**	**Plant height (cm)**	**Number of tillers plant^{-1}**	**Flag leaf length (cm)**	**Panicle length (cm)**	**Number of panicles plant^{-1}**	**Number of spikelets panicle^{-1}**	**Filled grains panicle^{-1}**	**Grain yield (kg ha^{-1})**	**1000 grain weight (g)**
08FAN 10	94.0	139.0	82.0	48.0	25.3	18.0	35.7	10.7	106.3	3,967	24.9
Basmati 217	97.3	136.0	136.0	62.0	43.0	29.0	53.0	11.7	127.3	5,877	26.4
Basmati 370	106.0	142.3	129.0	40.7	44.0	28.0	36.3	11.0	148.0	4,470	26.9
Dourado precoce	85.0	130.3	139.3	28.3	40.0	27.0	19.0	11.3	129.7	4,667	27.2
IR-27-93-80-1	118.3	157.0	78.3	61.7	27.0	21.7	44.7	13.0	107.7	3,157	24.5
K2-54	87.0	119.0	97.0	41.0	35.3	21.0	36.3	10.3	107.3	4,317	23.2
K2-8	85.0	112.0	95.0	60.3	34.3	21.7	48.0	10.3	100.0	4,543	24.5
K2-9	87.0	115.3	92.0	55.0	38.0	21.0	46.0	10.3	91.0	3,243	23.6
Komboka	102.7	141.3	91.0	50.7	25.7	20.3	34.3	14.0	115.3	3,910	24.1
NERICA 1	82.0	124.3	110.3	38.3	36.3	21.7	28.3	12.0	110.7	4,360	26.0
PAN 84	87.0	121.0	133.3	16.0	34.0	22.7	15.3	13.0	123.3	4,967	27.9
SARO 5	99.0	131.7	80.0	36.3	20.0	19.3	25.3	15.0	117.3	3,643	25.2
K54 x IR-27-93-80-1	79.0	115.0	82.0	48.0	25.0	22.0	41.0	13.0	132.0	3,850	23.9
K54 x Komboka	112.0	138.7	75.0	52.0	34.0	18.0	35.0	15.0	137.0	4,680	25.8
K54 x NERICA 1	81.7	122.3	88.3	39.7	35.0	20.3	37.0	11.3	126.3	5,040	24.9
K54 x PAN 84	79.7	112.7	103.0	30.3	35.3	22.3	27.7	13.3	120.7	4,340	27.2
K54 x SARO 5	124.0	144.3	99.0	55.0	40.3	21.3	40.3	14.7	144.7	5,057	23.9
K8 x 08 FAN 10	85.0	114.0	95.0	60.3	34.3	21.7	48.0	10.3	100.0	4,543	24.5
K8 x Basmati 217	97.0	136.0	114.7	45.7	35.0	24.3	36.3	10.7	128.7	6,107	26.7
K8 x Basmati 370	100.7	138.7	116.7	41.7	38.3	26.7	38.3	10.3	138.3	6,803	27.0
K8 x Dourado precoce	84.7	121.0	109.3	39.7	35.0	21.0	38.0	12.3	113.3	4,097	24.9
K8 x IR-27-93-80-1	84.3	128.3	85.7	54.3	32.0	21.7	47.7	11.7	131.3	4,450	24.1
K8 x Komboka	127.0	147.3	71.3	51.7	26.0	21.3	43.0	12.0	135.3	4,093	24.1
K8 x NERICA 1	76.0	119.7	89.7	39.7	29.7	20.7	33.0	9.7	89.7	4,237	26.3
K8 x PAN 84	85.3	118.0	116.7	35.3	38.3	21.0	35.3	11.0	135.7	5,567	25.1
K8 x SARO 5	99.0	131.7	80.0	36.3	20.0	19.3	25.3	16.3	117.3	3,643	25.2
K9 x 08FAN 10	94.0	139.0	82.0	48.0	25.3	18.0	35.7	10.7	106.3	3,967	24.9

Table 3.4 continued

Parents and crosses	50% Days to flowering	Days to maturity	Plant height (cm)	Number of tillers plant^{-1}	Flag leaf length (cm)	Panicle length (cm)	Number of panicles plant^{-1}	Number of spikelets panicle^{-1}	Filled grains panicle^{-1}	Grain yield (kg ha^{-1})	1000 grain weight (g)
K9 x Basmati 217	89.7	131.7	112.3	52.7	38.3	27.0	49.3	11.0	136.0	5,843	26.4
K9 x Basmati 370	94.0	136.3	120.3	45.0	36.3	22.7	41.7	11.7	138.7	6,100	25.0
K9 x Dourado precoce	83.3	125.7	123.3	31.7	37.7	25.0	30.0	11.7	132.3	4,840	27.2
K9 x IR-27-93-80-1	94.3	134.3	76.3	46.7	25.3	21.3	43.3	12.3	139.3	4,297	24.9
K9 x Komboka	89.3	133.3	111.3	88.0	33.3	23.0	74.3	12.3	150.3	5,060	23.8
K9 x NERICA 1	82.3	121.3	87.3	40.0	29.3	21.0	37.0	11.3	117.3	3,370	25.1
K9 x PAN 84	87.7	119.3	110.7	31.7	42.3	21.7	28.3	11.0	139.7	5,047	24.1
K9 x SARO 5	99.0	130.7	82.7	40.0	22.33	21.0	36.0	14.3	123.7	3,720	25.3
K54 x 08 FAN 10	87.7	121.3	87.3	43.3	38.3	20.7	39.3	11.0	120.0	5,010	23.0
K54 x Basmati 217	125.3	149.0	135.0	70.7	47.3	30.0	60.0	11.0	138.7	6,843	25.6
K54 x Basmati 370	59.7	110.7	155.0	77.0	34.7	26.3	55.3	10.7	83.3	5,437	24.8
K54 x Dourado precoce	95.7	109.7	86.0	31.0	26.7	18.3	24.7	10.3	81.3	6,120	27.1
Grand mean	**93.0**	**128.7**	**101.5**	**46.5**	**33.3**	**22.3**	**38.6**	**11.8**	**121.5**	**4,958**	**25.2**
CV %	**3.3**	**1.9**	**1.2**	**5.8**	**3.2**	**3.0**	**7.0**	**5.4**	**3.3**	**6.0**	**1.6**
LSD 5 %	**5.04**	**3.99**	**2.01**	**4.37**	**1.72**	**1.09**	**4.40**	**1.04**	**6.61**	**486.4**	**0.65**

LSD= Least significant differences of means at ($P \leq 0.05$), CV = Coefficient of variation

Table 3.5 Seed set of crosses between nine male indica and three female japonica rice varieties.

Crosses	Seed set (%)	Description
K9 x NERICA 1	27.3	Low percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K8 x NERICA 1	36.4	Low percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K54 x NERICA 1	26.3	Low percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K9 x SARO 5	36.4	Low percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K8 x SARO 5	72.7	Highest percentage of seed set. There was low genetic barrier between the indica and japonica rice parents
K54 x SARO 5	45.5	Average percentage of seed set. There was moderate genetic barrier between the indica and japonica rice parents
K9 x 08FAN 10	31.4	Low percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K8 x 08FAN 10	63.6	High percentage of seed set. There was low genetic barrier between the indica and japonica rice parents
K54 x 08FAN 10	54.6	Average percentage of seed set. There was moderate genetic barrier between the indica and japonica rice parents
K9 x Basmati 370	72.7	Highest percentage of seed set. There was low genetic barrier between the indica and japonica rice parents
K8 x Basmati 370	85.8	Highest percentage of seed set. There was low genetic barrier between the indica and japonica rice parents
K54 x Basmati 370	81.8	Highest percentage of seed set. There was low genetic barrier between the indica and japonica rice parents
K9 x Basmati 217	22.3	Low percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K8 x Basmati 217	98.2	Highest percentage of seed set. There was low genetic barrier between the indica and japonica rice parents
K54 x Basmati 217	16.2	Low percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K9 x PAN 84	9.1	Lowest percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K8 x PAN 84	18.2	Low percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K54 x PAN 84	45.5	Average percentage of seed set. There was moderate genetic barrier between the indica and japonica rice parents
K9 x Dourado	99.1	Highest percentage of seed set. There was low genetic barrier between the indica and japonica rice parents
K8 x Dourado	8.2	Lowest percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K54 x Dourado	72.7	Highest percentage of seed set. There was low genetic barrier between the indica and japonica rice parents
K9 x Komboka	90.9	Highest percentage of seed set. There was low genetic barrier between the indica and japonica rice parents
K8 x Komboka	27.3	Low percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K54 x Komboka	15.3	Lowest percentage of seed set. There was high genetic barrier between the indica and japonica rice parents
K9 x IR2729-80-1	63.6	High percentage of seed set. There was low genetic barrier between the indica and japonica rice parents
K8 x IR2729-80-1	10.1	Lowest percentage of seed set .There was high genetic barrier between the indica and japonica rice parents
K54 x IR2729-80-1	89.9	Highest percentage of seed set. There was low genetic barrier between the indica and japonica rice parents

3.6 Heterosis for agronomic and yield traits

3.6.1 Duration to 50 % flowering

Duration to 50 % flowering ranged from -32 % (K_2-54 x Basmati 370) to 55 % (K_2-8 x Komboka), early flowering plants were observed in the F_1 hybrids K_2-9 x NERICA 1 (-2 %), K_2-8 x NERICA 1 (-24 %), K_2-54 x Basmati 370 (-32 %), K_2-54 x PAN 84 (-5 %) and K_2-54 x IR-27-93-80-1 (-4 %), in contrast K_2-8 x Komboka (55 %), K_2-54 x Basmati 217 (52 %) and K_2-54 x SARO 5 (51 %) took longer days to flowering (Table 3.6).

3.6.2 Days to maturity

Days to maturity varied from -8 % (K_2-54 x Basmati 370) to 33 % (K_2-54 x Basmati 217) with K_2-54 x Basmati 217 (33 %) followed by K_2-8 x Komboka (32 %) and K_2-54 x SARO 5 (28 %) taking longer days to maturity while K_2-54 x Basmati 370 (-8 %) followed by K_2-54 x *Dourado precoce* (-4 %) took shorter duration maturity (Table 3.6).

3.6.3 Number of tillers per plant

The better parent heterosis for number of tillers per plant varied from -2 % (K_2-8 x *Dourado precoce*) to 90 % (K_2-9 x Komboka) with K_2-9 x Komboka (90 %) followed by K_2-54 x Basmati 217 (78 %) and K_2-54 x Basmati 370 (54 %) exhibiting the highest heterosis while K_2-54 x *Dourado precoce* (-24 %) and K_2-9 x PAN 84 (-22 %) had negative heterosis for number of tillers per plant (Table 3.6).

3.6.4 Panicle length

High better parent heterosis was observed in the hybrids K_2-8 x Basmati 370 (17 %), K_2-54 x Basmati 370 (13 %), K_2-9 x Basmati 217 (30 %), K_2-9 x Basmati 217 (18 %) and K_2-8 x Basmati 370 (17 %), in contrast K_2-54 x Komboka (-23 %) and K_2-54 x *Dourado precoce* (-22 %) exhibited negative heterosis for panicle length (Table 3.6).

3.6.5 Filled grains per panicle

Filled grains per panicle varied from -35 % (K_2-8 x Basmati 370) to 35 % (K_2-54 x Basmati 370) with K_2-54 x Basmati 370 (35 %) followed by K_2-9 x Komboka (23 %) and K_2-9 x PAN 84 (19

%) exhibiting high heterosis for filled grains while K_2-8 x Basmati 370 (-35 %) and K_2-8 x 08FAN 10 (-22 %) had negative heterosis for filled grains per panicle (Table 3.6).

3.6.6 Grain yield

The better parent heterosis for grain yield varied from -1 % (K_2-54 x SARO 5) to 31 % (K_2-9 x Basmati 370). The high yielding F_1 hybrids include; K_2-9 x Basmati 370 (31 %) followed by K_2-9 x Komboka (24 %), K_2-8 x Basmati 217 (23 %), K_2-54 x Basmati 217 (21 %), K_2-54 x *Dourado precoce* (20 %) and K_2-8 x Basmati 370 (18 %) in contrast K_2-9 x NERICA 1 (-28 %), K_2-9 x SARO 5 (-32 %) and K_2-9 x PAN 84 (-10 %) exhibited negative heterosis grain yield (Table 3.6).

Table 3.6 Heterosis for agronomic and yield traits in indica and japonica rice crosses.

	Earliness				Yield components						Grain yield			
Cross	50% Days to flowering	Better parent	Days to maturity	Better parent	Panicle length	Better parent	Number of tillers plant^{-1}	Better parent	Number of panicles plant^{-1}	Better parent	Filled grains panicle^{-1}	Better parent	Grain yield plot^{-1}	Better parent (kg ha^{-1})
K9 x NERICA 1	-2%	82	8%	112	-13%	23	-7%	39	-19%	43	-6%	127	-28%	4,360
K8 x NERICA 1	-24%	84	1%	124	-9%	21	0%	41	-14%	28	-15%	110	-14%	4,280
K54 x NERICA 1	2%	82	12%	118	-9%	20	-7%	40	-16%	30	-13%	120	-10%	4,620
K9 x SARO 5	22%	86	18%	131	-13%	19	0%	36	-19%	27	-8%	117	-32%	3,643
K8 x SARO 5	20%	85	20%	130	-13%	20	-7%	37	-37%	26	-9%	120	-32%	3,639
K54 x SARO 5	51%	99	28%	129	-9%	21	34%	41	-7%	25	16%	121	-1%	3,680
K9 x 08FAN 10	15%	94	24%	139	-26%	18	22%	48	-26%	36	-17%	106	-29%	3,967
K8 x 08FAN 10	4%	82	0%	138	-4%	21	44%	47	12%	38	-22%	109	-14%	3,887
K54 x 08FAN 10	7%	90	8%	140	-9%	19	7%	49	-9%	40	-8%	110	-11%	3,680
K9 x Basmati 370	15%	82	21%	142	0%	29	17%	41	7%	37	8%	148	31%	5,470
K8 x Basmati 370	22%	85	23%	140	17%	30	2%	40	-12%	40	-35%	142	18%	5,281
K54 x Basmati 370	-32%	106	-8%	141	13%	28	54%	42	2%	38	35%	150	-13%	5,681
K9 x Basmati 217	10%	82	18%	136	18%	29	29%	62	14%	53	6%	127	0%	4,877
K8 x Basmati 217	13%	97	23%	138	4%	27	17%	64	2%	50	2%	129	23%	4,688
K54 x Basmati 217	52%	82	33%	135	30%	29	78%	61	40%	49	7%	128	21%	4,680
K9 x PAN 84	7%	87	6%	121	-4%	23	-22%	16	-33%	15	19%	123	-10%	5,680
K8 x PAN 84	5%	82	4%	123	-9%	24	-12%	17	-14%	16	8%	124	0%	5,680
K54 x PAN 84	-5%	87	2%	122	-4%	22	-24%	18	-35%	14	-7%	126	-27%	4,967
K9 x Dourado precoce	0%	85	12%	130	9%	27	-24%	28	-30%	19	2%	130	-16%	4,686
K8 x Dourado precoce	2%	82	7%	129	-9%	26	-2%	31	-12%	20	-13%	129	-28%	4,683
K54 x Dourado precoce	17%	82	-4%	131	-22%	28	-24%	29	-49%	18	2%	127	20%	5,680
K9 x Komboka	7%	102	19%	141	0%	20	90%	51	70%	34	23%	116	24%	3,682
K8 x Komboka	55%	99	32%	139	-9%	21	29%	50	2%	36	4%	115	-26%	3,910
K54 x Komboka	37%	82	24%	142	-23%	20	27%	52	-23%	37	8%	114	-12%	3,680
K9 x IR-27-93-80-1	16%	118	21%	157	-9%	21	15%	61	2%	43	9%	107	-23%	3,167
K8 x IR-27-93-80-1	5%	112	13%	156	-4%	23	37%	60	9%	44	3%	110	-18%	3,085
K54 x IR-27-93-80-1	-4%	82	3%	158	-4%	22	17%	62	-5%	43	4%	109	-32%	3,680

3.7 General combining ability (GCA) effects of the parents

3.7.1 Duration to 50 % flowering

Additive variance for days to 50 % flowering (926.4) was higher than the dominance variance (677.9). Komboka (16.959*), SARO 5 (14.8*), Basmati 217 (11.5*) and K_2-54 (1.4) contributed positive GCA effects for 50 % days to flowering suggesting longer days to flowering while NERICA 1 (-12.5), PAN 84 (-8.3), Basmati 370 (-7.7), IR-27-93-80-1 (-6.60), *Dourado precoce* (-4.6) and K_2-9 (-2.1) exhibited negative GCA effects (Table 3.7). The male variance was higher (1127) than the female variance (90.8) for this trait (Table 3.3).

3.7.2 Days to maturity

Additive variance for days to maturity (509.68) was higher than dominance variance (344.54). Komboka (12.1*), Basmati 217 (11.2*) and SARO 5 (7.9*) exhibited high and positive GCA effects and took longer days to maturity while NERICA 1 (-6.6), PAN 84 (-11.0), *Dourado precoce* (-8.9) and K_2-54 (-2.9) had negative GCA effects suggesting early maturity (Table 3.7). The male variance was higher (668.7) than the female variance (194.8) for this trait (Table 3.3).

3.7.3 Plant height

Dominance variance for plant height (814.8) was higher than the additive variance (524.3). Basmati 370 (24.7**), Basmati 217 (16.7*) and PAN 84 (8.2*) exhibited positive GCA effect for plant height while IR-27-93-80-1 (-14.9), SARO 5 (-10.1), 08FAN 10 (-9.4), NERICA 1 (-9.2), Komboka (-11.2) and K_2-8 (-2.2) displayed negative GCA effects for plant height indicating that these parents were short statured plants (Table 3.7). The male variance was higher (2805.8) than the female variance (98.3) for this trait (Table 3.3).

3.7.4 Panicle length

Dominance variance for panicle length (17.4) was higher than the additive variance (8.86). Basmati 370 (2.4**) and Basmati 217 (3.8**) displayed positive GCA effect for panicle length suggesting longer panicles while K_2-8 (-0.2), Komboka (-1.0), *Dourado precoce* (-0.5), PAN 84 (-0.4) and NERICA 1 (-1.1) exhibited short panicles due to negative GCA effects for panicle length (Table 3.7). The male variance was higher (51.5) than the female variance (0.8) for this trait (Table 3.3).

3.7.5 Flag leaf length

Dominance variance for flag leaf length (136.3) was higher than the additive variance (18.9). Basmati 217 (7.1*), PAN 84 (5.5*), Basmati 370 (3.3*) and K_2-54 (2.0*) had positive GCA effects for flag leaf length while *Dourado precoce* (-0.1), Komboka (-2.1), K_2-8 (-1.1), K_2-9 (-0.9), SARO 5 (-5.6) and NERICA 1 (-1.8) exhibited negative GCA effects for flag leaf length (Table 3.7). The male variance was higher (183.2) than the female variance (82.2) for this trait (Table 3.3).

3.7.6 Number of tillers per plant

Additive variance for number of tillers (769.2) was higher than the dominance variance (523.3). Komboka (9.9*), Basmati 217 (5.5*), Basmati 370 (4.4*) and K_2-54 (2.4*) exhibited positive GCA effects for number of tillers plant^{-1} while *Dourado precoce* (-7.9), PAN 84 (-8.9), SARO 5 (-2.1), NERICA 1 (-4.5) and K_2-9 (-0.2) had fewer tillers due to negative GCA effects for number of tillers per plant (Table 3.7). The male variance was higher (1000.4) than the female variance (149.9) for this trait (Table 3.3).

3.7.7 Number of spikelets per panicle

Additive variance for number of spikelets (11.4) was higher than the dominance variance (4.9). SARO 5 (2.4*) and Komboka (1.1*) displayed positive GCA effects for number of spikelets while Basmati 370 (-1.5**) exhibited negative GCA effects for number of spikelets per panicle (Table 3.7). The male variance was higher (19.9) than the female variance (2.7) for this trait (Table 3.3).

3.7.8 Number of panicles per plant

Additive variance for number of panicles (457.4) was higher than the dominance variance (357.7). The parents Komboka (10.7**), Basmati 217 (8.5*), Basmati 370 (5.1*) and K_2-9 (1.7*) had positive GCA effects for number of panicles per plant while *Dourado precoce* (-9.2), PAN 84 (-9.6), SARO 5 (-6.2) and NERICA 1 (-4.4) had fewer number of panicles due to negative GCA effects for number of panicles per plant (Table 3.7). The male variance was higher (520.8) than the female variance (78.4) for this trait (Table 3.3).

3.7.9 Filled grains per panicle

Additive variance for filled grains per panicle (1354.7) was higher than the dominance variance (1118.7). Komboka (16.6**), Basmati 217 (10.2**), IR-27-93-80-1 (9.9**), PAN 84 (7.7**) and K_2-9 (7.3*) had positive GCA effects for filled grains per panicle while 08FAN 10 (-15.5), NERICA 1 (-13.2), Basmati 370 (-4.8), *Dourado precoce* (-15.3) and K_2-54 (-4.1) displayed negative GCA effects (Table 3.7). The male variance was higher (1379.8) than the female variance (1068.4) for this trait (Table 3.3).

3.7.10 Grain yield

Additive variance for grain yield (473) was higher than the dominance variance (283). Basmati 370 (1017.9**), Komboka (66.5*), Basmati 217 (902.5**) and K_2-54 (140.0**) had high and positive GCA effect for grain yield while SARO 5 (-506.8), K_2-8 (-160), 08FAN 10 (-368.3), NERICA 1 (-457.2) and IR-27-93-80-1 (-468.1) exhibited negative GCA effects for yield (Table 3.7). The male variance was higher (686) than female variance (630) for this trait (Table 3.3).

3.7.11 1000-grain mass

Basmati 217 (1.1**), PAN 84 (0.3**), *Dourado precoce* (1.3**) and K_2-8 (0.2*) had significant GCA effects for 1000 grain mass while IR-27-93-80-1 (-0.9), 08FAN 10 (-0.8), Basmati 370 (-0.2) and K_2-54 (-0.2) had lighter 1000 grain mass because these genotypes exhibited negative GCA effects for 1000 grain mass (Table 3.7). The male variance was higher (5.4) than the female variance (0.8) for this trait (Table 3.3).

Table 3.7 General combining ability (GCA) effects of 12 rice parents for different agronomic traits.

Genotype	**50% Days to flowering**	**Days to maturity**	**Plant height (cm)**	**Panicle length (cm)**	**Flag leaf length (cm)**	**Number of tillers plant^{-1}**	**Number of spikelet's panicle^{-1}**	**Number of panicles plant^{-1}**	**Number of filled grains panicle^{-1}**	**Grain yield (kg ha^{-1})**	**1000 grain mass (g)**
Males											
NERICA 1	-12.49	-6.59	-9.15	-1.13	-1.84	-4.46	-0.73	-4.37	-13.16	-457.2	0.23
IR-27-93-80-1	-6.60	-1.81	-14.85	-0.36	-5.73	1.46	0.51	3.96	9.95**	-468.1	-0.87
SARO 5	14.84*	7.85*	-10.13	-1.21	-5.62	-2.07	2.39**	-6.15	4.28	-506.8	-0.34
08 FAN 10	-3.60	-3.59	-9.42	-1.55	-0.51	1.99	-0.82	0.96	-15.49	-368.3	-0.81
Basmati 370	-7.72	0.85	24.71**	2.37*	3.27*	4.38*	-1.45**	5.07*	-4.83	1017.9**	-0.24
Basmati 217	11.51*	11.19*	16.69*	3.81**	7.05*	5.45*	-0.91	8.52*	10.17**	902.5**	1.08**
PAN 84	-8.27	-11.04	8.23*	-0.36	5.49*	-8.85	0.07	-9.59	7.73*	-78.04	0.31*
Dourado precoce	-4.60	-8.93	5.11	-0.53	-0.06	-7.86	-0.20	-9.15	-15.27	70.8	1.25**
Komboka	16.95*	12.07*	-11.20	-1.04	-2.06	9.97*	1.14*	10.74**	16.62**	66.5*	-0.61
Females											
K_2-8	0.73	0.37	-2.19	-0.17	-1.10	-2.27	-0.36	-1.7037	-3.20	-160.0	0.16*
K_2-54	1.36	-2.85	1.33	0.01	2.01**	2.43*	0.2	-1.4E-14	-4.05	140.0**	-0.17
K_2-9	-2.09	2.48	0.85	0.16	-0.91	-0.16	0.12	1.703*	7.25*	200.0	0.01

* Significance at 5 % level of probability, ** Significance at 1 % level of probability

3.8 Specific combining ability effects of the 27 F_1 hybrids for agronomic and yield traits

3.8.1 Days to maturity

K_2-54 x SARO 5 (11.6**), K_2-8 x Basmati 370 (10.1**), K_2-54 x Basmati 217 (14.1**) and K_2-8 x Komboka (11.0**) had positive SCA effects for days to maturity. In contrast K_2-54 x IR-27-93-80-1 (-11.27**), K_2-54 x Basmati 370 (-17.0) and K_2-54 x *Dourado precoce* (-12.3) had negative SCA effects (Table 3.8). This trait exhibited an SCA variance of 574.9 (Table 3.3).

3.8.2 Plant height

K_2-54 x Basmati 370 (30.4), K_2-54 x Basmati 217 (18.4), K_2-9 x *Dourado precoce* (18.3) and K_2-9 x Komboka (22.6) had high SCA effects for plant height while K_2-54 x *Dourado precoce* (-18.9) and K_2-8 x Komboka (-17.3) expressed negative SCA effects (Table 3.8). This trait exhibited an SCA variance of 612.6 (Table 3.3).

3.8.3 Panicle length

K_2-8 x Basmati 370 (2.1), K_2-54 x Basmati 217 (3.9) and K_2-9 x *Dourado precoce* (3.3) had positive SCA effects for panicle length while K_2-54 x *Dourado precoce* (-3.2) and K_2-54 x Komboka (-2.9) displayed negative SCA effects (Table 3.8). This trait exhibited an SCA variance of 13.5 (Table 3.3).

3.8.4 Flag leaf length

K_2-54 x SARO 5 (9.6**), K_2-54 x Basmati 217 (10.9**) and K_2-9 x PAN 84 (6.6**) expressed highly significant SCA effects while K_2-54 x IR-27-93-80-1 (-5.5**), K_2-8 x SARO 5 (-10.5**), K_2-9 x SARO 5 (-8.2**), K_2-54 x *Dourado precoce* (-6.4**) and K_2-8 x Komboka (-6.2**) showed negative SCA effects for flag leaf length (Table 3.8). This trait exhibited an SCA variance of 103.3 (Table 3.3).

3.8.5 Number of tillers per plant

K_2-54 x Basmati 217 (17.6), K_2-54 x Basmati 370 (24.8), K_2-8 x 08FAN 10 (10.9) and K_2-9 x Komboka (30.1) had high SCA effects for number of tillers plant^{-1} while K_2-54 x *Dourado precoce* (-8.2), K_2-9 x PAN 84 (-6.6) and K_2-8 x Basmati 217 (-6.9) had negative SCA effects (Table 3.8). This trait exhibited an SCA variance of 433.0 (Table 3.3).

3.8.6 Number of spikelets per panicle

K_2-54 x Komboka (1.9), K_2-54 x PAN 84 (1.4) and K_2-9 x Basmati 370 (1.3) had positive SCA effects for number of spikelets panicle^{-1} while K_2-54 x Basmati 370 (-2.4) exhibited negative SCA effect for the same trait (Table 3.8). This trait exhibited an SCA variance of 4.1 (Table 3.3).

3.8.7 Number of panicles per plant

K_2-9 x Komboka (28.3), K_2-54 x Basmati 217 (15.4) and K_2-54 x Basmati 370 (12.5) had high SCA effects for number of panicles plant^{-1} while K_2-54 x *Dourado precoce* (-10.7) and K_2-54 x Komboka (-9.7) expressed negative SCA effects (Table 3.8). This trait exhibited an SCA variance of 302.7 (Table 3.3).

3.8.8 Filled grains per panicle

K_2-8 x Basmati 370 (16.2**), K_2-9 x Basmati 370 (14.5**) and K_2-9 x Komboka (17.9**) had positive SCA effects for filled grains per panicle while K_2-54 x *Dourado precoce* (-35.6), K_2-8 x 08FAN 10 (-17.4) and K_2-8 x NERICA 1 (-28.4) had negative SCA effects for the same trait (Table 3.8). This trait had an SCA variance of 857.4 (Table 3.3).

3.8.9 Grain yield

K_2-9 x Komboka (1995.1*), K_2-9 x Basmati 370 (1121.9*), K_2-54 x *Dourado precoce* (1090.4*) and K_2-54 x Basmati 217 (986.5*) had high SCA effects for grain yield. K_2-9 x Komboka was the highest grain yielder and it originated from high x high GCA combination while the rest of the crosses originated from either high x low or low x high GCA combinations (Table 3.8). This trait exhibited an SCA variance of 242 (Table 3.3).

3.8.10 1000-grain mass

K_2-9 x *Dourado precoce* (1.6***), K_2-54 x *Dourado precoce* (1.6***), K_2-54 x PAN 84 (1.9***), K_2-8 x Basmati 370 (1.8***) and K_2-8 x NERICA 1 (0.9***) had high SCA effects for 1000 grain mass while K_2-9 x Komboka (-1.2**), K_2-9 x PAN 84 (-1.1**) and K_2-54 x Basmati 370 (-2.2**) showed negative SCA effects for the same trait (Table 3.8). This trait showed an SCA variance of 4.4 (Table 3.3).

Table 3.8 Specific combining ability (SCA) effects of 27 F_1 hybrids for different agronomic and yield characters.

Crosses combination	50% Days to flowering	Days to maturity	Plant height (cm)	Panicle length (cm)	Flag leaf length (cm)	Number of tillers plant^{-1}	Number of spikelet's panicle^{-1}	Number of panicles plant^{-1}	Number of filled grains panicle^{-1}	Grain yield (kg ha^{-1})	1000 grain weight (g)
K_2-8 x NERICA1	-9.54	-3.95	-1.03	-0.33	-2.65	-3.04	-1.19	-4.83	-28.37***	-208.2	0.98**
K_2-54 x NERICA1	-4.01	-1.36	-2.36	-0.65	2.62	-3.04	0.34	-0.96	7.68	540.0	-0.36
K_2-9 x NERICA1	-3.36	-2.33	-3.36	-0.01	-2.98	-2.71	0.34	-0.96	-3.31	-1038.6*	-0.14
K_2-8 x IR-27-93-80-1	-4.50	1.67	0.67	-0.11	1.38	5.52	-0.50	5.58	3.84	-6.66	-0.84*
K_2-54x IR-27-93-80-1	-9.70	-11.27***	-2.99	0.22	-5.54***	-0.68	0.73	-0.86	4.66	-568.2	-1.02***
K_2-9 x IR-27-93-80-1	5.26	7.50	-8.64	-0.43	-5.21*	-1.98	0.12	1.40	9.65	-136.0	0.01
K_2-8 x SARO5	-1.43	-0.74	-9.70	-1.54	-10.53***	-8.64	0.85	-11.43***	-7.76	-740.0	0.14
K_2-54 x SARO5	22.95***	11.55***	9.25	0.39	9.58***	9.62	0.54	3.06	19.15***	624.9	-1.07***
K_2-9 x SARO5	-1.43	-1.71	-7.04	0.07	-8.23***	-5.05	0.24	-1.13	-3.58	-655.7	0.20
K_2-8 x FAN10	-5.42	-13.14***	4.55	1.04	1.37	10.86*	-0.49	7.26	-17.39***	-575.9	-0.48
K_2-54 x FAN10	-2.82	-4.08	-3.09	0.08	5.33*	-5.76	0.12	-1.11	2.34	266.6	-1.20***
K_2-9 x FAN10	3.36	13.06***	-8.41	-2.49***	-7.53***	-1.20	-0.19	-4.66	-13.21	-552.1	-0.05
K_2-8 x Basmati 370	12.02*	10.14***	-7.88	2.09*	3.65	-9.73	0.08	-3.93	16.17***	875.9	1.82***
K_2-54 x Basmati 370	-27.98***	-17.04***	30.35***	1.77	0.02	24.82***	-2.37***	12.49***	-39.45***	-471.8	-2.24***
K_2-9 x Basmati 370	5.52	7.88	-4.22	-1.77	1.67	-6.47	1.30*	-0.71	14.47*	1121.9*	-0.09
K_2-8 x Basmati 217	-1.64	1.52	-1.87	-1.56	-1.32	-6.86	-1.02	-7.42	1.15	338.2	1.24***
K_2-54 x Basmati 217	26.00***	14.14***	18.40***	3.91***	10.88***	17.59***	0.20	15.44***	11.10	986.5*	0.17
K_2-9 x Basmati 217	-8.79	-2.69	-4.20	1.01	1.97	-0.01	0.20	5.14	6.31	28.4	0.90**
K_2-8 x PAN84	-2.65	-2.97	8.56	-0.75	2.66	-2.98	-0.70	-0.22	8.91	702.83	-0.13
K_2-54 x PAN84	-8.18	-8.15	-5.07	0.54	-0.30	-7.87	1.44***	-7.63	-5.61	-320.52	1.91***
K_2-9 x PAN84	-0.37	-1.68	2.58	-0.11	6.62***	-6.57	-0.70	-6.98	10.80	204.61	-1.13***
K_2-8 x Dourado precoce	-5.22	-1.29	4.36	-0.58	1.83	0.28	0.77	2.16	-4.43	-848.2*	-0.52
K_2-54 x Dourado precoce	5.51	-12.29***	-18.91***	-3.16***	-6.41***	-8.19	-1.07	-10.72***	-35.58***	1090.4*	1.56***
K_2-9 x Dourado precoce	-6.52	3.24	18.32***	3.27***	4.47	-7.54	0.16	-5.57	12.15	-136.0	1.63***
K_2-8 x Komboka	24.77***	11.00***	-17.27***	0.23	-6.18***	-5.41	-0.76	-1.98	5.29	-778.7	-0.84*
K_2-54 x Komboka	10.14	3.59	-13.62	-2.99***	1.73	-5.09	1.99***	-9.71***	7.08	-285.2	0.76
K_2-9 x Komboka	-11.97***	-1.59	22.62***	1.84	1.07	30.11***	-0.46	28.29***	17.95***	1995.1***	-1.21***

* Significance at 5 % level of probability, ** Significance at 1 % level of probability, *** Significance at $P \leq 0.001$ level of probability

3.8.11 Correlations between parents and their crosses for agronomic traits

There were significant ($P \leq 0.05$) correlations among the agronomic and yield characters (Table 3.9 and 3.10). The correlation analysis among the parental lines showed that grain yield was strongly correlated with number of panicles per plant (r = 0.36**), filled grains per panicle (r = 0.43**), number of tillers (r = 0.32**) and flag leaf length (r = 0.83***). Among the F_1 hybrids, grain yield was strongly correlated with number of panicles per plant (r = 0.45***) and number of tillers (r = 0.50***). However, grain yield was negatively correlated with days to maturity (r = -0.03) and 50 % days to flowering (r = -0.01*). Filled grains per panicle was strongly correlated with panicle length (r = 0.73***) and 1000-grain mass (r = 0.73***).

Table 3.9 Correlations among parental lines for agronomic and yield traits.

	Days to maturity (days)	Filled grains panicle^{-1}	Flag leaf length (cm)	Grain yield (kg ha^{-1})	Number of panicles plant^{-1}	Number of spikelets panicle^{-1}	Number of tillers plant^{-1}	Plant height (cm)	Panicle length (cm)	50% Days to flowering (days)
Filled grains panicle^{-1}	0.40	-								
Flag leaf length (cm)	-0.23	0.39*	-							
Grain yield (kg ha^{-1})	-0.03	0.43**	0.83***	-						
Number of panicles plant^{-1}	0.13	-0.34*	0.20	0.36**	-					
Number of spikelets	0.34*	0.16	-0.55**	-0.45**	-0.38*	-				
Number of tillers plant^{-1}	0.26	-0.41*	-0.01	0.32**	0.94***	-0.21	-			
Plant height (cm)	-0.11	0.69***	0.79***	0.65***	-0.29	-0.18	-0.45**	-		
Panicle length (cm)	0.19	0.73***	0.81***	0.80***	0.14	-0.24	-0.01	0.83***	-	
50% Days to flowering	0.87***	0.27	-0.30	-0.01	0.29	0.36*	0.38*	-0.30	0.09	-
Thousand grain weight	0.12	0.73***	0.39*	0.31	-0.52**	0.13	-0.59**	0.79***	0.59***	-0.09

* Significant correlation at 5 % level of probability, ** Significant correlation at 1 % level of probability

Table 3.10 Correlations among the F_1 hybrids for agronomic and yield traits.

	Days to maturity (days)	Filled grains panicle^{-1}	Flag leaf length (cm)	Grain yield (kg ha^{-1})	Number of panicles plant^{-1}	Number of spikelets panicle^{-1}	Number of tillers plant^{-1}	Days to maturity (days)	50% Days to flowering (days)	Plant height (cm)
Filled grains panicle^{-1}	0.59***	-								
Flag leaf length (cm)	0.09	0.33**	-							
Thousand grain weight	0.02	-0.06	0.05	-						
Grain yield (kg ha^{-1})	-0.23*	0.25*	0.58***	0.16	-					
Number of panicles plant^{-1}	0.27*	0.25*	0.26*	0.45***	0.43***	-				
Number of spikelets	0.31**	0.46***	-0.26*	0.01	-0.34**	-0.19	-			
Number of tillers plant^{-1}	0.29**	0.11	0.18	0.50***	0.37***	0.93***	-0.15	-		
50% Days to flowering	0.82***	0.47***	0.09	0.08	0.16	0.05	0.44***	0.11	-	
Plant height (cm)	-0.08	0.13	0.67***	0.03	0.61***	0.36***	-0.49***	0.32**	-0.24*	-
Panicle length (cm)	0.20	0.25*	0.57***	0.13	0.53***	0.50***	-0.37***	0.39***	0.02	0.753***

* Significant correlation at 5 % level of probability, ** Significant correlation at 1 % level of probability

3.9 DISCUSSION

3.9.1 Estimate of genetic components

The analysis of variance for combining ability showed that the rice genotypes differed significantly for all the agronomic and yield traits studied. There are two types of gene action i.e. additive and non-additive gene action. Additive gene action is also known as breeding value (BV) (Mishra et al., 2017). It is defined as the parental value of an individual as the contributor of genes to the next generation. It only represents the proportion of the genotypic value that is transmitted from parent to the progeny (Mishra et al., 2017). Non-additive gene action results from the interaction between genes that represents the different degree of dominance and epistasis (Wang et al., 1998). Further analysis of GCA/SCA variances showed that the nature of gene action was additive due to high magnitude of fixable genetic component for days to 50 % flowering, days to maturity, number of tillers plant^{-1}, number of spikelet's panicle^{-1}, number of effective tillers plant^{-1}, number of fertile grains panicle^{-1} and grain yield. Non-additive gene action was dominant for plant height, panicle length, flag leaf length and 1000-grain weight. These results are contrary to the findings of Sathya and Jebaraj (2015) who reported dominance of non-additive gene action for all the agronomic traits studied under aerobic condition. Major role of non-additive gene effects in the inheritance of agronomic and yield traits were reported (Muhammad *et al.,* 2010; Hasan *et al.,* 2013; Hasan *et al.,* 2015). Previous studies have reported predominant role of additive gene action in the control of yield traits (Chakraborty *et al.,* 2009; Satheesh *et al.,* 2010; Gnanamalar and Vivekanandan, 2013). The combining ability analysis revealed significant GCA and SCA variance for most of the agronomic characters studied suggesting the importance of both additive and non-additive gene actions in the expression of the yield traits. Previous studies reported the significance of both additive and non-additive gene action in the expression of agronomic traits (Mirarab *et al.,* 2011; Padmavathi *et al.,* 2012; Dar *et al.,* 2014 and Malemba *et al.,* 2017).

3.9.2 Evaluation of parents based on GCA effects

The rice parents such as Basmati 370, Basmati 217, K_2-54 and Komboka had high and positive GCA effects for grain yield suggesting that these parental genotypes were good general combiners for grain yield. Previous studies also reported good general combiners for agronomic and yield traits in rice genotypes (Padmavathi *et al.,* 2012; Raju *et al.,* 2014; Sathya and Jebaraj, 2015). The parental genotypes such as Basmati 370, Basmati 217, PAN 84 and Komboka exhibited high and positive GCA effects for panicle length, flag leaf length, number of tillers plant^{-1}, number of spikelet's panicle^{-1}, number of panicles plant^{-1} and number of filled grains panicle^{-1} suggesting their desirability for improvement of positive agronomic and yield traits because they contributed to high grain yield, in contrast parents with low and negative GCA estimates (NERICA 1, PAN 84, K_2-9, *Dourado precoce* and K_2-54) are preferred for improvement of negative traits of grain yield such as plant height, 50 % days to flowering and days to maturity. Previous studies reported the significance of using parents with high and positive GCA effects for the improvement of positive agronomic traits (Mirarab *et al.*, 2011; Raju *et al.,* 2014; Malemba *et al.*, 2017). This study revealed high GCA variances for days to 50 % flowering, days to maturity, number of tillers plant^{-1}, number of spikelet's panicle^{-1}, number of effective tillers plant^{-1}, number of fertile grains panicle^{-1} and grain yield.

Mirarab et al., (2011) conducted a study on heterosis, combining ability and genetic parameters of yield and yield components in rice. They reported that GCA was only significant for total number of kernels per panicle, number of filled grains and grain yield per plant implying that additive gene action was predominant in the control of these traits. Previous research also reported the predominance of additive gene action in the inheritance of days to maturity, number of productive tillers plant^{-1}, number of panicles per plant and 1000 grain weight (Dar et al., 2014).Therefore, it is suggested that a breeding method that would take care of the fixable gene effects and as well as maintain heterozygosity for exploiting the dominance effects may be more efficient for the improvement of grain yield (Chakraborty *et al.,* 2009). Hence, a simple selection procedure followed by pedigree breeding is sufficient to improve the traits influenced by additive gene action (Chakraborty *et al.*, 2009).

3.9.3 Evaluation of F_1 hybrids based on SCA effects

The hybrids K_2-9 x Komboka, K_2-9 x Basmati 370, K_2-54 x *Dourado precoce* and K_2-54 x Basmati 217 were good specific combiners for grain yield. All the high yielding F_1 hybrids (K_2-9 x Komboka, K_2-9 x Basmati 370, K_2-54 x *Dourado precoce* and K_2-54 x Basmati 217) originated from high x high GCA combinations attributable to additive x additive type of gene actions thus the yield potential of these hybrids can be fixed in subsequent generations (Sandhyakishore *et al.*, 2011). Negative SCA effects for grain yield was observed among some of the hybrids K_2-9 x NERICA 1, K_2-8 x *Dourado precoce* and K_2-8 x Komboka suggesting low yield potential these hybrids. The hybrid K_2-9 x NERICA 1 originated from high x low GCA combination while the rest of the crosses with low and negative SCA effects originated from low x high GCA combinations. The high yield potential observed in the hybrids with high x low GCA combinations could be attributed to interaction between positive alleles in the good combiner and negative alleles in the poor combiner (Chakraborty et al., 2009). This study revealed that hybrids (K_{2}-54 x Basmati 217, K_{2}-54 x Komboka, and K_{2}-54 x Basmati 370) that originated from high general combiner parents with high and positive SCA estimates are expected to produce desirable transgressive segregants which can be recognized by carrying out pedigree breeding method (Muhammad *et al.,* 2010). High SCA effects of hybrids (K_2-9 x NERICA 1) from high x low GCA combining parents would be unfixable in subsequent generations and hence cannot be exploited by pedigree selection procedure (Sathya and Jebaraj, 2015), but in later generations these hybrids would produce desirable transgressive segregants upon modification of the conventional breeding methodology to accommodate both additive and non-additive genetic effects (Chakraborty et al., 2009). The present investigation revealed that parents with high GCA estimates were not always the best general combiners, furthermore, the results also indicated that parents with high GCA effects (Basmati 217, K_2-54, Basmati 370 and Komboka) were the best general combiners for only a specific trait but none of the parents or the specific crosses were best for all the characters studied. Previous studies reported similar results (Chakraborty et al., 2009 and Malemba et al., 2017).

3.9.4 Heterosis for agronomic and yield traits

3.9.4.1 Days to maturity

The F_1 hybrids K_2-54 x Basmati 217, K_{2}-8 x Komboka and K_2-54 x SARO 5 were late maturing while K_2-54 x Basmati 370, K_2-54 x *Dourado precoce* were early maturing over the better parent (NERICA 1) suggesting the possibility of developing early maturing lines. Development of early maturing and high yielding rice varieties are desired in rice breeding program. Negative heterosis is desirable for days to 50 % flowering and days to maturity implying that hybrids with negative heterosis over better parent are early maturing. Tiwari et al., (2011) observed better parent heterosis in five superior hybrids (IR58025A x IR35454-18-1-1-2R, NMS4A x IET9352, NMS4A x IR35454-18-1-1-2R, NMS4A x IR42686-2-118-6-2R and IR58025A x IR32419-28-3-

1-3R) for early flowering. Borah et al., (2017) reported a significant negative mid parent heterosis, heterobeltiosis and standard heterosis over the late maturing pure line Ranjit in 55 cross combinations.

3.9.4.2 Number of tillers per plant

K_2-9 x Komboka, K_2-54 x Basmati 217 and K_2-54 x Basmati 370 had high number of tillers per plant in contrast K_2-54 x *Dourado precoce* and K_2-9 x PAN 84 had fewer number of tillers. Panicle bearing tillers have a strong correlation with grain yield thus leading to high crop productivity. Therefore, positive heterosis is desirable for effective tiller plant^{-1}.

Joshi (2001) studied better parent heterosis and standard heterosis in 14 F_1 hybrids generated between improved and local rice cultivars and three wild aborted male sterile parents and he reported high better parent heterosis for number of tillers in nine F_1 hybrids.

Borah et al., (2017) studied the performance of 60 F_1 hybrids along with 23 parents and three standard commercial checks in India during the cropping season of 2013 and they reported a significant and positive better parent heterosis for effective tillers per plant and standard heterosis in 16 F_1 hybrids.

3.9.4.3 Panicle length

K_2-8 x Basmati 370, K_2-54 x Basmati 370, K_2-9 x Basmati 217, K_2-9 x Basmati 217 and K_2-8 x Basmati 370 had longer panicles while K_2-54 x Komboka and K_2-54 x *Dourado precoce* had the shortest panicle length. Large panicles are normally associated with high number of grains panicle^{-1} resulting in high grains yields. Therefore, hybrids with positive heterosis for panicle length are desirable. Tiwari et al., (2011) reported a relatively low better parent heterosis of 0.37 % for panicle length over the better parent. Out of 60 F_1 hybrids evaluated, 20 hybrids showed higher panicle length over the better parent and 16 crosses exhibited high panicle length over the standard variety. Lokaprakash et al., (1992) and Singh et al., (1992) observed both positive and negative heterosis for panicle length.

3.9.4.4 Filled grains per panicle

K_2-54 x Basmati 370, K_2-9 x Komboka and K_2-9 x PAN 84 had high number of filled grains per panicle in contrast K_2-8 x Basmati 370 and K_2-8 x 08FAN 10 had the lowest filled grains.

The number of fertile grains panicle^{-1} is directly associated to grain yield and therefore a positive heterosis would be desirable in order to increase the productivity of rice varieties.

Tiwari et al., (2011) carried out line x tester mating design involving three CMS lines and 20 elite restorers to identify the best heterotic combination and they observed that most of the hybrids that exhibited superiority over the better parent or standard variety for grain yield also displayed significant better parent heterosis for filled grains panicle^{-1} and number of spikelets panicle^{-1}.

Borah et al., (2017) studied the performance of 60 F$_1$ hybrids along with 23 parents and three standard commercial checks at Assam Agricultural University in India. They reported significant and positive better parent heterosis in the hybrid IR58025A x IET18648 (49.73 %) and standard heterosis of 141.1 % over the check variety TTB404 for number of filled grains panicle^{-1}.

3.9.4.5 Grain yield

The high yielding F$_1$ hybrids include; K$_{2}$-9 x Basmati 370, K$_{2}$-9 x Komboka, K$_{2}$-8 x Basmati 217, K$_{2}$-54 x Basmati 217, K$_{2}$-54 x *Dourado precoce* and K$_{2}$-8 x Basmati 370 in contrast K$_{2}$-9 x NERICA 1, K$_{2}$-9 x SARO 5 and K$_{2}$-9 x PAN 84 were low grain yielders. The hybrid vigour for grain yield was due to interaction of many yield components such as days to maturity, panicle length, number of tillers plant^{-1}, number of panicles plant^{-1} and filled grains panicle^{-1}.

Grafius (1959) reported that grain yield is a complex trait and it is a multiplicative end product of several yield components. In this study, crosses with hybrid vigour for grain yield exhibited heterotic effect along with hybrid vigour for panicle length, number tillers plant^{-1}, number of panicles plant^{-1} and fertile grains panicle^{-1}. Swaminathan et al., (1972) reported that heterosis of more than 20 % over better parent could offset the cost of hybrid seed production.

Rahimi et al., (2010) studied heterosis for grain yield and yield components for 15 F$_1$ hybrids generated by half diallel crosses of six diverse rice cultivars. They reported a significant better parent heterosis for grain yield in the hybrid Dorfak x Domsefid.

Bhati et al., (2015) evaluated 32 F$_1$ hybrids at Agricultural Research Farm in India for performance and heterosis for grain yield and yield components to identify the best hybrid combination for commercial utilization and they reported that the magnitude of heterosis for grain yield over better parent was significantly superior to 21 hybrids with highest value of 93.3 % observed in the cross Pusa6A x Akshaya Dhan.

3.9.5 Conclusion

In this study, Basmati 370, Basmati 217, Komboka and K_2-54 and their hybrids K_2-9 x Komboka, K_2-9 x Basmati 370, K_2-54 x *Dourado precoce* and K_2-54 x Basmati 217 have considerable potential that can be exploited to develop rice varieties with high yield potential by using a pedigree selection procedure. The results further showed that some good combiners for grain yield turned out to be poor specific combiners as shown in the crosses K_2-54 x Komboka, K_2-54 x Basmati 370 and K_2-9 x Basmati 217 reflecting negative SCA effect and negative heterosis. However, parents with high x high, low x high GCA combinations were found to be the best genotypes since they reflected high and positive SCA effects for grain yield. The non-significant SCA effect displayed by some crosses for various yield traits could be due to the presence of unfavourable genetic combinations of the parents for agronomic and yield characters.

CHAPTER FOUR

EVALUATION OF $F_{2.3}$ FAMILIES FOR GRAIN YIELD, EARLINESS AND GRAIN QUALITY

4.0 ABSTRACT

Improvement of grain yield is one of the major objectives in rice breeding program worldwide. Consumption of locally produced rice in eastern Africa is low because most smallholder farmers rely on local rice cultivars which have low yield potential, late maturing and poor cooking and eating qualities. As a result urban consumers prefer imported rice at the expense of the locally produced rice. However, the imported rice is expensive and unaffordable to the rural poor. Therefore, improving the grain yield, earliness and culinary qualities of the local cultivars will increase consumption of locally produced and affordable rice as well as its competitiveness in the local market. The objective of this study was to evaluate the $F_{2.3}$ families for yield potential, earliness and grain quality.

The study materials were segregating F_2 populations developed between indica and japonica parents during the long rain season between March and June 2014 using a 6 x 6 half diallel mating design without reciprocals. The choice of the crosses was based on yield potential, resistance to diseases and drought tolerance. The 16 F_2 segregating populations and six commercial checks were evaluated at Mwea Research Station and Kirogo Experimental Farm during the short rain season of 2016. Seven outstanding F_3 families were selected and further evaluated during the long rain season between April and July 2017. Data was collected on agronomic and yield traits and analyzed using Genstat 15th edition statistical software.

The physico-chemical characteristics of the $F_{2.3}$ families were analyzed at the Food Science Laboratory of University of Nairobi.

The results showed significant ($P \leq 0.05$) genetic variation among the $F_{2.3}$ families for days to 50 % flowering (89.6-104.9 days), days to maturity (120.8-139.6 days), plant height (89.9-100.8 cm), panicle length (21.0-21.7 cm), and flag leaf length (27.3-30.3 cm), number of tillers plant^{-1} (21.5-29.3), number of spikelet's panicle^{-1} (10.4-12.2), number of panicles plant^{-1} (18.8-27.8), and number of filled grains panicle^{-1} (107.5-129.9), grain yield (4,080-9,350 kg ha^{-1}) and 1000 grain mass (22.9-24.9 g).

Highly significant variation ($P \leq 0.001$) was observed for days to 50 % flowering (77.4**), plant height (1298.2**), panicle length (80.1**), and flag leaf length (1110.9***), number of tillers plant^{-1} (3009.1***), number of panicles plant^{-1} (4041.5***), and filled grains panicle^{-1} (2672***) and grain yield (30.5**) across sites. The $F_{2.3}$ families of WAB-56-104 x NERICA 4, NERICA 4 x MWUR 4, NERICA 4 x NERICA 1 and NERICA 10 x KUCHUM were relatively early maturing (120-122 days), exhibited short to intermediate plant height (97-102 cm) and consistently maintained higher yields (5,180-9,020 kg ha^{-1}) across locations compared to the popular check variety Basmati 370.

The results of the physico-chemical analysis revealed that the $F_{2.3}$ families of NERICA 4 x MWUR 4, NERICA 4 x NERICA 1 and NERICA 10 x KUCHUM had slender grain shape while NERICA 4 x MWUR 4, NERICA 4 x NERICA 1 and WAB-56-104 x NERICA 4 had soft cooked texture and recorded low gelatinization temperatures (55-69^{o}C) and cooked fast (22.3-23.3 minutes).

The sensory assessment revealed that the $F_{2.3}$ families of WAB-56-104 x NERICA 4, NERICA 4 x MWUR 4, MWUR 4 x NERICA 4 and CG 14 x NERICA 10 were slightly aromatic while those of NERICA 4 x NERICA 1, NERICA 13 x K45 and NERICA 10 x KUCHUM were non-aromatic. The check variety Basmati 370 was outstanding for physical grain quality and aroma compared to the non-Basmati rice genotypes. Therefore, the sensory panel preferred the check variety Basmati 370 as far as aroma was concerned suggesting that Basmati 370 has implication for future breeding. From the 16 populations evaluated, three families namely MWUR 4 x NERICA 4, NERICA 4 x NERICA 1 and WAB-56-104 x NERICA 4 exhibited better agronomic, culinary and physico-chemical qualities. However, there is need to advance these $F_{2.4}$ families for further selection in order to ascertain their agronomic, culinary and physico-chemical qualities.

Key words: Aroma, culinary qualities, grain quality, grain yield, rice (*Oryza sativa*)

4.1 INTRODUCTION

Rice is the second most important food crop globally after maize and provides over 20 % of the daily calorie intake for 3.9 billion people globally (Kohnaki et al., 2013). Food and Agricultural Organization (FAO) reported that the world rice requirement by 2050 will be 943.6 million t which requires an annual increase of about 5.8 million t from the present level of production. Annual rice production in Africa was estimated at 31 million t from 11 million hectares under cultivation (FAO, 2017). The annual demand and production of rice in Sub-Saharan Africa is estimated at 12 and 10.2 million t respectively while the annual population growth in the region is estimated at 2.6 % (FAO, 2017). The increasing demand of rice consumption in the Sub-Saharan Africa is attributed to rapid population growth, increasing urbanization as well as the relative ease of preservation and cooking (Macauley and Ramadjita, 2015). The African rice requirement by 2050 will be 99.2 million t which requires an annual increase of about 0.1 % from the present level of production. Development of both lowland and upland rice varieties with high yield potential and durable resistance to both biotic and abiotic stresses can contribute to the realization of this target (Dogara and Jumare, 2014).

Rice breeding focuses mainly on yield improvement, breeding for tolerance to biotic and abiotic stresses. However, little attempts have been made to breed for grain quality in Eastern Africa (Kimani, 2010). Rice consumers in eastern Africa prefer imported to locally produced rice. This is attributed to poor nutritional and cooking quality of the locally produced rice (Njiruh *et al.*, 2013). The smallholder farmers grow traditional rice cultivars that have low yield potential, late maturing, highly susceptible to rice yellow mottle virus and rice blast. Grain quality of these landraces does not meet consumer preferences and market demand. Therefore, it is important to identify outstanding rice varieties through characterization of the available upland rice varieties which can be used directly to improve productivity and culinary quality of local rice cultivars grown by smallholder farmers.

Grain quality is one of the key parameters used by farmers while selecting for a suitable rice variety for commercial production. A preferred rice variety should not only have good agronomic performance but also high grain quality that is widely acceptable to farmers, millers and consumers. Consumer preference for rice is based on physical properties such as appearance after cooking and aroma, grain shape and grain size while the cooking and textural properties of the rice grain is dependent on chemical composition of the rice cultivar (Umadevi et al., 2010). Consumer preference for grain shape and size varies. Some consumers prefer short, bold grain while others prefer medium long grain (Dela Cruz and Khush, 2000), but long slender grain is preferred by consumers in Kenya (MoA, 2014).

Previous studies suggested that long rice grains are highly preferred and fetch premium price at the international market (Dela Cruz *et al.,* 2002). The cooking and eating qualities of rice can be influenced by aroma, amount of amylose content, gel consistency and gelatinization temperature (Dela Cruz *et al.,* 2002). Juliano (1993) reported a positive and significant association between gelatinization temperature and cooking time, but gelatinization temperature is negatively co-related with the texture of cooked rice. Dela Cruz and Khush (2000) reported that rice varieties with higher gelatinization temperature normally have low amylose content. Consumers prefer rice grain with intermediate amylose content and low gelatinization (IRRI, 2000). Therefore, this study was conducted to select for yield potential, earliness and grain quality in $F_{2:3}$ rice families.

4.2 MATERIALS AND METHODS

4.2.1 Study location

The field experiments were conducted at Mwea Research Station and Kirogo Experimental Farm. The location of the research station has been described in Section 3.2.1.

4.2.2 Experimental site

The field experiments were conducted in an upland rainfed ecosystem during the short rain season between September and December 2016 at two different locations, i.e. Mwea Research Station and Kirogo Experimental Farm. The two locations have an average rainfall of about 850 mm divided into long rains between March and June and short rains between October and December. The temperature varies between 15.6^{o}C to 28.6^{o}C. Mwea Research Station lies on a latitude 0 37’S and Longitude 37 20’E at an elevation of 1159 m above sea level and the soil type is a nitosol with a pH of about 5.65. Kirogo Experimental Farm lies on latitude 0 38’S and longitude 37 22’E on an altitude of 1150 m above sea level. The soil type is a vertisol with a pH of about 5.07 (KARI, 2000).

4.2.3 Germplasm

The genotypes evaluated comprised of 16 F_2 populations (Table 4.1) developed at Mwea Research Station during the long rain season between March and June 2014 using a 6 x 6 half diallel mating design without reciprocals (Griffing, 1956). A total of 12 parents were included in the crossing block with six male and six females respectively. The objective of these crosses was to generate F_2 populations segregating for grain yield, resistance to rice blast, grain quality and drought tolerance. The parents were planted in buckets at the hybridization nursery in Mwea Research Station to produce the F_1 seeds that were subsequently selfed to produce 30 F_2 populations during the short rain season between September and December 2015. The outstanding F_2 populations were selected using pedigree breeding method and evaluated at Mwea Research Station and Kirogo Experimental Farm during the cropping season of 2017 to generate the $F_{2:3}$ rice families.

Table 4.1 The F_2 segregating populations used in the study and their characteristics.

Crosses	Characteristics	Reference
MWUR 4 x KOMBOKA	MWUR 4 - high yield (7 t ha^{-1}); Komboka - grain quality, high adaptability to local conditions	KALRO, 2014
MWUR 4 x NERICA 4	MWUR 4 - high yield (7 t ha^{-1}); NERICA 4 - blast tolerance and long grains	KALRO, 2014
NERICA 4 x MWUR 4	NERICA 4 - blast tolerance and long grains; MWUR 4 - high grain yield (7 t ha^{-1})	KALRO, 2014
WAB-56-104 x KUCHUM	WAB-56-104 - high grain yield (8 t ha^{-1}), good grain quality; KUCHUM - blast tolerance, earliness	KALRO, 2014
NERICA 4 x KOMBOKA	NERICA 4 - blast tolerance, long grains; Komboka - grain quality, high adaptability to local conditions	KALRO, 2014
WAB-56-104 x NERICA 4	WAB-56-104 - high grain yield (8 t ha^{-1}), good grain quality; NERICA 4 - blast tolerance, long grains	KALRO, 2014
CG 14 x NERICA 10	CG 14 - earliness, mild aroma; NERICA 10 - long grains, blast tolerance	KALRO, 2014
NERICA 4 x NERICA1	NERICA 4 - blast tolerance, long grains; NERICA 1 -earliness, aroma	KALRO, 2014
NERICA 10 x KUCHUM	NERICA 10 - long grains, blast tolerance; KUCHUM - blast tolerance, earliness	KALRO, 2014
K_2-62 x K_2-34	K_2-62 - high yielding (5.4 t ha^{-1}), earliness; K_2-34 - well adapted to irrigated lowlands upland areas	KALRO, 2014
DUORADO x K_2-114	DUORADO - moderate yielding (4.1 t ha^{-1}), good	KALRO,

	cooking; K_2-114 - high yielding (6.7 t ha^{-1}), earliness	2014
NERICA 10 x MWUR 4	NERICA 10 - long grains, blast tolerance; MWUR 4 - high yield (7 t ha^{-1})	KALRO, 2014
NERICA 13 x K_1-45	NERICA 13 - long grains, non-aromatic, tolerance to leaf blast; K_1-45 - high yielding (7.6 t ha^{-1}), earliness and well adapted to irrigated lowlands upland areas	KALRO, 2014
GSR 32 x TAI	GSR 32 - earliness, short stature; TAI - good grain quality, tolerance to blast	KALRO, 2014
K_2-1 x MWUR 2	K_2-1 - earliness and well adapted to irrigated lowlands upland areas; MWUR 2 - high yield (6.5 t ha^{-1})	KALRO, 2014
K_1-45 x BS370	K_1-45 - high yielding (7.6 t ha^{-1}), earliness and well adapted to irrigated lowlands upland areas; BS370 - good grain quality	KALRO, 2014

4.2.4 Experimental design and crop husbandry

The F_2 seeds were planted alongside six commercial checks (Basmati 370, NERICA 1, 4, 10, MWUR 4 and KUCHUM) in a randomized complete block design with three replications at Mwea Research Station and Kirogo Experimental Farm between March and July 2017. The experimental plots were partitioned into smaller plots of 5 m by 5 m in size and the seeds were planted in a row length of 3 m. Each plot had 16 rows (240 plants plot^{-1}). The seeds were sown using direct seeding method with an inter-row spacing of 20 cm and intra-row spacing of 20 cm with two seeds per hill. Gapping and thinning was done when the seedlings were 2-3 weeks old. One seedling per hill was left to ensure uniform plant density. Hand weeding was done at 20, 40 and 60 days after planting. DAP fertilizer (18:46:0) was applied during planting at a rate of 50 kg N ha^{-1} and 40 kg P ha^{-1}. First top dressing was carried out at active tillering using NPK (17:17:17) fertilizer applied at a rate of 120 kg N ha^{-1}, 30 kg P ha^{-1} and 90 kg K ha^{-1}. Calcium ammonium nitrates (CAN) fertilizer was applied at panicle initiation stage at a rate of 100 kg N ha^{-1}. Pesticide (Duduthrin 1.75 EC, Lambda-cyhalothrin 17.5 g/L) was applied every two weeks to control stem borer, fall armyworm and leaf hoppers at a rate of 50 ml/20 L of water.

4.3 DATA COLLECTION

The agronomic traits were collected according to the procedure outlined in Standard Evaluation System (SES) for rice (IRRI, 2013). Data was collected on days to 50 % flowering, days to maturity, plant height, number of tillers plant^{-1}, number of effective tillers plant^{-1}, flag leaf length, panicle length, number of spikelet's plant^{-1}, number of fertile grains panicle^{-1}, grain yield and 1000 grain mass on individual plot basis as described in Section 3.2.6.

4.4 Determination of grain quality traits

4.4.1 Grain length

Ten milled rice kernels, unbroken, firm and without cracks were selected from each genotype. The length and width of the kernels was determined using a vernier caliper (Model 530-312, Mitutoyo, Tokyo). Average length and breadth of the kernels were calculated (Suganthi and Nacchair, 2015). The length of the rice kernels were classified as very long (more than 7.5 mm), long (6.61 to 7.5 mm), intermediate (5.51 to 6.6 mm) and short (≤ 5.5 mm) (Dela Cruz and Khush, 2000).

Figure 4.1 Vernier caliper used to measure kernel length and width

4.4.2 Grain shape

The length to breadth ratio (L/B) of ten milled kernels was determined by dividing the mean length of each kernel by its corresponding breadth (Suganthi and Nacchair, 2015). The L/B ratio was calculated as follows: $\frac{\text{Average length of rice kernel (mm)}}{\text{Average breadth of rice kernel (mm)}}$...……………….........Equation 8

The L/B ratios were used to determine the grain shape as suggested by Osamu and Badi, (2013). Grain shape of the rice kernels were categorized as slender (over 3.0), medium (2.1 to 3.0), bold (1.1 to 2.0) and round (≤ 1.0) (IRRI, 2000).

4.4.3 Determination of Alkali Spreading Value (ASV)

Alkali spreading value refers to the extent of spreading of milled rice kernels in a dilute alkali solution (1.7 % KOH).

It is used to estimate the gelatinization temperature of starch (Dela Cruz and Khush, 2000). The alkali spreading value was determined using the procedure described by Little et al., (1958). A set of six whole rice kernels without cracks were selected for each genotype. There were placed in a petri-dish and soaked in 10 ml of 1.7 % (0.3035 M) potassium hydroxide (KOH) solution. The kernels were carefully separated from each other using forceps to provide enough space between kernels to allow for spreading. The petri-dishes were covered and incubated at 30˚C for 16 to 24 hours in an oven. The starchy endosperm was rated visually based on a seven (7) point numerical spreading scale as follows: 1- grain not affected; 2- grain swollen; 3- grain swollen, collar incomplete and narrow; 4- grain swollen, collar complete and wide; 5- grain split, collar complete and wide; 6- grain dispersed, merging with collar; 7- grain completely dispersed and intermingled (IRRI, 2000).

The gelatinization temperature of the rice varieties was determined by relating the kernel spreading values with the corresponding temperature range. The temperatures normally vary between 50^{o}C to 79^{o}C, and are classified as low (55 to 69°C); intermediate (70 to 74°C) and high 75 to 79°C (Dela Cruz and Khush, 2000).

4.4.4 Determination of gel consistency (GC)

Gel consistency measures the tendency of the cooked rice to harden after cooking. Rice varieties with soft gel consistency are preferred and the cooked grains normally have high degree of tenderness. Gel consistency was determined according to the procedure described by Cagampang et al., (1973). 100 mg of rice flour from each genotype was placed in (13 x 100 mm) test tubes and 0.2 ml of 95 % ethanol containing 0.25 % thymol blue indicator was added. The mixture was shaken for 30 seconds using vortex shaker. About 2.0 ml of 0.2 N of KOH solutions was added immediately. The tubes were fitted with glass marbles and placed in water bath at 100^{o}C for 8 minutes. The test tubes were removed from the water bath and allowed to stand at a room temperature for 5 minutes. The cooled tubes were placed in ice cold water for 20 minutes. All the test tubes were laid horizontally over a graph paper and the total gel length was measured in millimeters from the bottom of the test tubes after 45 minutes. Gel consistency of the rice kernels were classified as follows: soft gel (61 to 100 mm), medium (41 to 60 mm) and hard gel (26 to 40 mm) (IRRI, 2000).

4.4.5 Aroma test

Five grams of milled rice was taken from each genotype and soaked in 10 ml 1.7 % KOH solution at room temperature in a covered glass petri-plate for about 1 hour. The soaked rice kernels were rated on a scale of 1 to 4 by a test panel as follows: 1- no aroma; 2- slight aroma; 3- moderate aroma; and 4- strong aroma (Krishnan and Bhonsle, 2010).

4.4.6 Cooking time

Five grams of milled rice from each genotype was poured into 135 ml of boiling distilled water in a 400 ml beaker. After every ten minutes of boiling, 5 to 10 kernels were randomly taken out with a ladle and pressed between two petri dishes. The grains were considered cooked when they no longer have opaque centres and the time was recorded. The cooking time was determined using the formula: Cooking time = Final time - Initial time (Oko et al., 2012).

4.5 DATA ANALYSIS

4.5.1 Analysis of variance

The analysis of variance for agronomic and grain quality traits were computed according to Gomez and Gomez (1984) using Genstat 15th edition statistical software. The variates were subjected to analysis of variance (ANOVA) using genotype, site and season as factors. Genotypic means were separated using the least significant differences (LSD) at $P \leq 0.05$. The ratios of range of LSD were calculated according to Iqbal and Clarke (2003) to select variables that best decide variation within the $F_{2.3}$ families.

4.5.2 Correlation analysis

Association among agronomic and grain quality traits were determined according to Pearson (1986). Linear correlation coefficient is given by $P_{xy} = \sigma_{xy}/\sigma_x\sigma_y$.....................................Equation 9

Where: $\sigma_x\sigma_y$= population standard deviations and σ_{xy}= population variance

4.6 RESULTS

4.6.1 Weather data

The amount of rainfall during the field experiments varied from 0.0 to 32.2 mm. Daily maximum temperatures ranged from 27.3 to 50.26°C and the minimum temperature varied from 12.6 to 27.3°C. The relative humidity varied between 22.0 and 99.5 %. The amounts of rainfall required for optimum growth of rice in a growing season is 850 mm and a total of about 1500 mm of rainfall per year. However the amounts of rainfall during the field experiment was very low (32.2 mm) for optimum growth of rice. Therefore, supplemental irrigation was applied using sprinklers at a rate of 12.39 mm per week for a period of four months. Daily temperature was relatively high for the growth and development of rice since the temperature required for optimal rice growth ranges from 20 to 38°C.

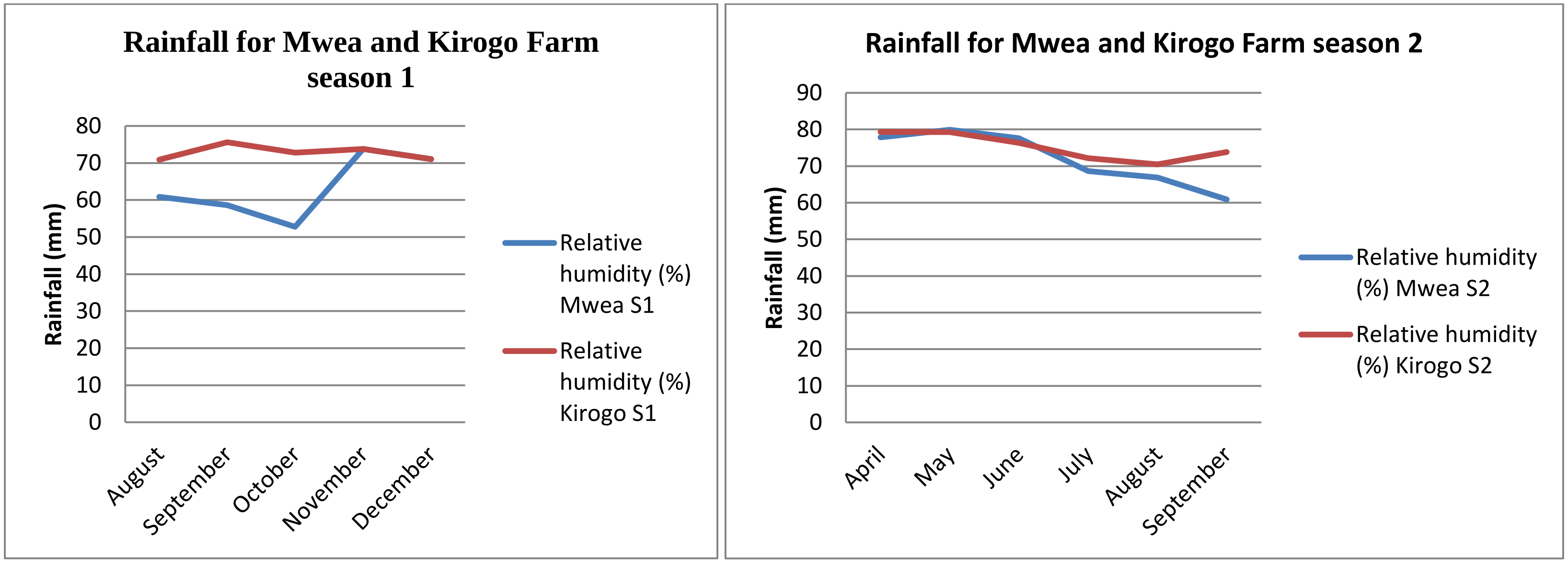
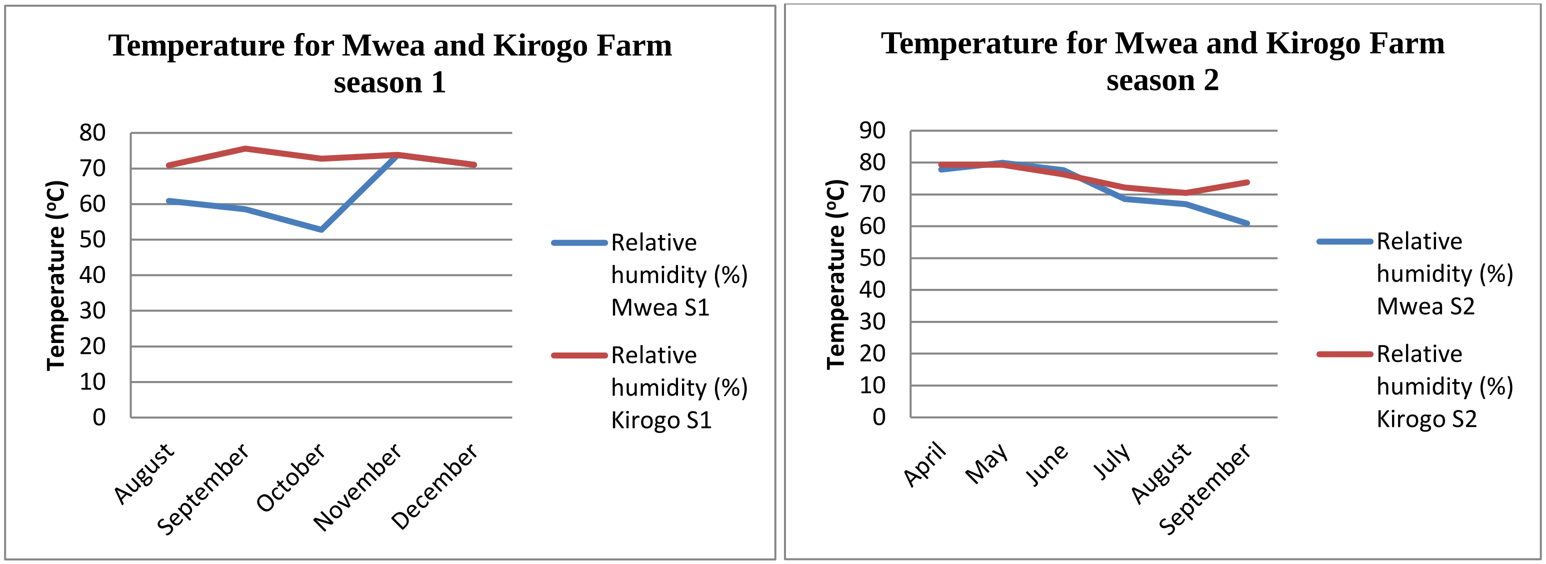
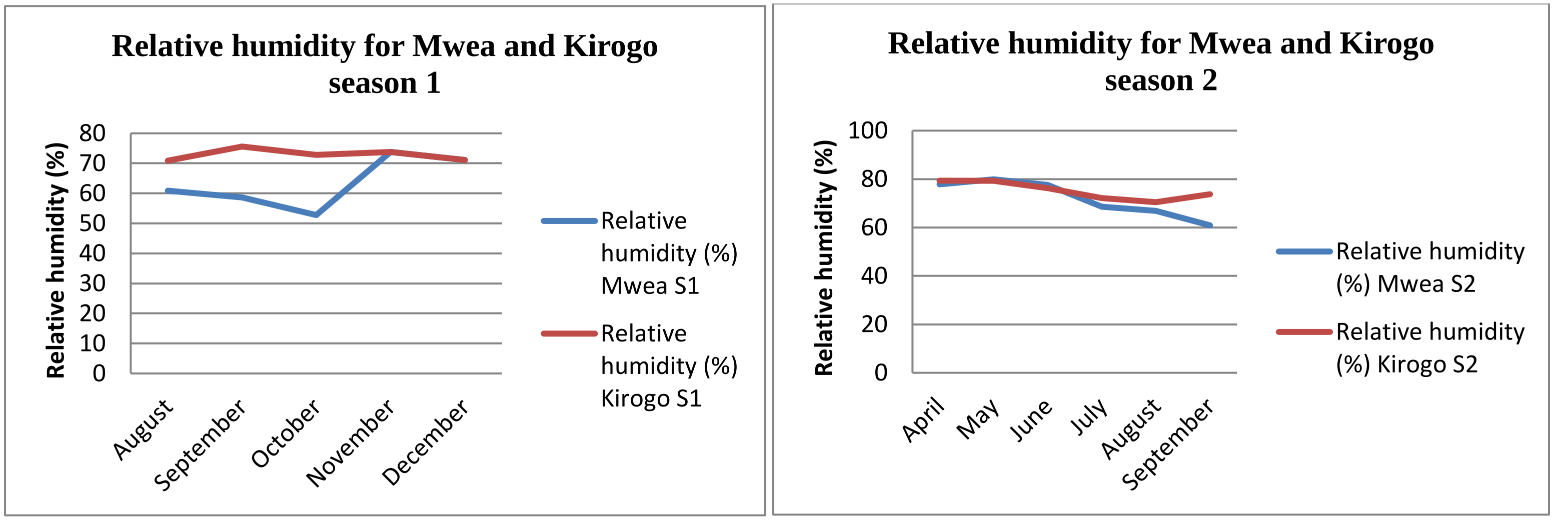


Figure 4.2 Rainfall data for Mwea and Kirogo Experimental Farm during season 1 and 2


Temperature for Mwea and Kirogo Farm season 1

Temperature for Mwea and Kirogo Farm season 2

Figure 4.3 Temperature for Mwea and Kirogo Experimental Farm during season 1 and 2


Relative humidity for Mwea and Kirogo season 1

Relative humidity for Mwea and Kirogo season 2

Figure 4.4 Relative humidity for Mwea and Kirogo Experimental Farm during season 1 and 2

4.6.2 Agronomic performance of $F_{2.3}$ families across environments

4.6.2.1 Duration to 50 % flowering and days to maturity

Duration to 50 % flowering showed significant ($P \leq 0.05$) seasonal (1141.9*), location (77.4*) and genotypic differences (346.9***) among the $F_{2.3}$ families. Highly significant interaction ($P \leq 0.001$) was observed for seasons x sites (933.4**), seasons x genotypes (40.9**), sites x genotypes (55.9***) and season x site x genotype (43.4***) among the $F_{2.3}$ families for days to 50 % flowering (Table 4.2). Generally the $F_{2.3}$ families took longer days to flower during the long rain seasons with an average mean of 93.6 for Mwea Research Station and 95.1 d for Kirogo Experimental Farm. The $F_{2.3}$ families at Kirogo Experimental Farm took relatively short duration to reach 50 % flowering with an overall mean of 90.1 d compared to Mwea Research Station (91.5 d) for the same growing period. Duration to 50 % flowering varied from 89.7 to 104.9 d. The $F_{2.3}$ families of WAB-56-104 x NERICA 4 (89.7 d) followed by NERICA 4 x NERICA 1 (90.1 d), NERICA 10 x KUCHUM (90.7 d) and NERICA 4 x MWUR 4 (91.6 d) flowered early while NERICA 13 x K 45 (104.9 d) took longer days to reach 50 % flowering across environments. Compared to all the $F_{2.3}$ families, the check variety Basmati 370 took relatively longer days to flower across sites (Table 4.3 and 4.4).

Table 4.2 Mean squares for agronomic and yield traits of $F_{2.3}$ families grown at Mwea and Kirogo Farm during 2016 short rain and 2017 long rain season.

		Mean squares				
Source of variation	**D.f**	**50% Days to flowering (Days)**	**Days to maturity (days)**	**Plant height (cm)**	**Number of tillers plant^{-1}**	**Flag leaf length (cm)**
Replication	2	9.58	10.30	60.79	21.83	7.71
Seasons	1	1141.93*	6.88	947.63*	154.29	366.10***
Residual	2	12.70	12.76	14.48	23.86	1.74
Sites	1	77.36*	0.38	1298.15**	3009.1***	1110.9***
Seasons x Sites	1	933.43***	61.93*	424.34*	265.01**	25.93*
Residual	4	11.02	7.42	23.21	11.12	1.21
Genotypes	13	346.99***	459.23***	190.03***	72.87***	20.15***
Seasons x Genotypes	13	40.90***	57.10***	83.23***	18.29***	32.72***
Sites x Genotypes	13	55.97***	85.88***	58.96***	46.95***	15.82***
Season x Site x Genotype	13	43.35***	35.22***	30.02***	20.75***	14.45***
Residual	104	10.39	6.42	6.22	4.93	2.62

D.f= degrees of freedom, * Significance at $P \leq 0.05$, ** Significance at $P \leq 0.001$, *** Significance at $P \leq 0.0001$

Table 4.2 continued

		Mean squares					
Source of variation	**D.f**	**Panicle length (cm)**	**Number of panicles plant^{-1}**	**Number of spikelets panicle^{-1}**	**Filled grains panicle^{-1}**	**Grain yield (kg ha^{-1})**	**1000 grain weight (g)**
Replication	2	2.38	27.61	0.10	300.0	530	1.70
Seasons	1	17.36*	14.88	2.15	3886.1*	714*	116.17**
Residual	2	0.66	9.58	0.88	225.3	150	0.08
Sites	1	80.10***	4041.5**	0.72	2672.0***	3045**	0.05
Seasons x Sites	1	6.10**	126.88*	0.48	1141.9*	190	7.98*
Residual	4	0.15	6.63	3.16	77.2	250	0.71
Genotypes	13	1.27	109.16***	2.74**	960.4***	2099***	8.15***
Seasons x Genotypes	13	3.42***	41.48***	3.03**	506.1***	700*	1.60
Sites x Genotypes	13	3.80***	45.41***	2.55**	406.3***	377***	2.58***
Season x Site x Genotype	13	1.95**	9.84*	3.11***	712.5***	620*	0.8
Residual	104	0.68	4.72	1.04	111.6	330	1.03

D.f= degrees of freedom, * Significance at $P \leq 0.05$, ** Significance at $P \leq 0.001$, *** Significance at $P \leq 0.0001$

Table 4.3 Agronomic performance of $F_{2.3}$ families at Mwea Research Station and Kirogo Experimental Farm

	Agronomic traits								Yield traits		
Genotype	**Days to 50% flowering**	**Days to maturity**	**Plant height (cm)**	**Number of tillers plant^{-1}**	**Flag leaf length (cm)**	**Panicle length (cm)**	**Number of panicles plant^{-1}**	**Number of spikelets panicle^{-1}**	**Number of filled grains panicle^{-1}**	**Grain yield (t ha^{-1})**	**1000 grain weight (g)**
Basmati 370 (check)	82.33	117.50	87.17	20.92	25.50	21.00	18.17	11.33	110.67	4.43	22.83
NERICA 4 (check)	87.33	131.17	92.33	23.33	26.67	21.83	22.50	12.33	111.50	4.80	22.60
KUCHUM (check)	92.17	129.42	93.58	22.67	27.83	20.92	19.67	12.25	115.67	3.94	22.67
MWUR 4 (check)	87.17	128.33	93.67	19.83	24.33	21.17	18.00	11.00	115.50	5.72	22.62
WAB-56-104 (check)	88.42	124.75	99.58	22.42	28.67	21.17	20.50	11.75	125.33	6.56	23.12
NERICA 1 (check)	83.83	119.17	87.83	24.00	26.50	21.50	22.00	10.03	105.17	5.35	24.56
NERICA 10 (check)	82.00	121.83	83.50	16.17	26.33	21.50	15.00	11.00	100.33	4.01	20.54
NERICA10 x KUCHUM	90.67	120.83	93.50	22.58	28.75	21.67	21.17	11.50	116.08	5.85	23.60
NERICA13 x K45	104.9	139.58	100.75	22.83	30.25	21.17	20.25	10.42	107.50	4.08	22.92
MWUR4 x NERICA4	95.17	130.00	95.33	21.67	27.25	21.50	18.83	11.83	129.92	5.02	24.39
NERICA4 x MWUR4	91.58	126.25	93.42	22.42	28.50	21.33	21.75	11.08	119.83	6.05	23.51
NERICA4 x NERICA1	90.08	123.33	95.83	21.50	27.33	21.00	21.08	11.75	118.17	6.76	23.71
CG14 x NERICA10	94.08	135.08	89.83	29.33	29.58	21.25	24.50	11.08	122.83	4.73	23.64
WAB-56-104 x NERICA4	89.67	121.58	94.92	28.33	28.42	21.17	27.83	12.17	128.75	9.35	24.99
Grand mean	**90.81**	**126.07**	**93.39**	**22.65**	**28.04**	**21.32**	**21.31**	**11.71**	**119.05**	**5.69**	**23.47**
LSD 5 %	**3.7**	**2.93**	**3.03**	**2.68**	**1.83**	**0.93**	**2.53**	**1.21**	**12.13**	**0.65**	**1.15**
CV %	**3.6**	**2.0**	**2.8**	**10.4**	**5.7**	**3.8**	**10.4**	**9.0**	**8.9**	**9.9**	**4.3**

LSD= Least significant differences of means at ($p \leq 0.05$), CV = Coefficient of variation

Table 4.4 Duration to 50 % flowering (days) of $F_{2.3}$ families grown at Mwea and Kirogo Farm during short rains of 2016 and long rains of 2017.

	Location/Season					
Genotype	**Mwea**			**Kirogo**		
	Long rain	Short rain	Mean	Long rain	Short rain	Mean
Basmati 370 (check)	106.3	100.0	99.7	104.0	95.0	97.5
WAB-56-104 (check)	92.0	88.7	90.3	95.0	78.0	86.5
KUCHUM (check)	97.3	97.3	97.7	87.7	86.7	87.2
MWUR 4 (check)	97.3	91.3	91.3	94.3	83.0	83.0
NERICA 1 (check)	84.3	82.7	84.7	86.3	83.0	83.0
NERICA 10 (check)	92.0	85.7	85.7	89.7	78.3	78.3
NERICA 4 (check)	93.3	89.3	89.3	93.0	85.3	85.3
NERICA10 x KUCHUM	94.3	91.0	92.7	97.0	80.3	88.7
NERICA13 x K45	111.3	103.0	107.7	108.0	97.3	102.7
NERICA4 x MWUR4	95.3	89.0	92.2	94.0	88.0	91.0
NERICA4 x NERICA1	89.7	88.0	88.8	99.3	83.3	91.3
MWUR4 x NERICA4	95.7	90.7	93.2	101.0	93.3	97.2
CG14 x NERICA10	94.3	91.0	92.7	101.7	89.3	95.5
WAB-56-104 x NERICA4	87.7	87.3	87.5	100.3	83.3	91.8
Grand mean	**93.6**	**89.4**	**91.5**	**95.1**	**85.2**	**90.1**
LSD 5 %	**4.74**	**4.12**	**4.37**	**8.59**	**1.92**	**5.99**
CV %	**3.1**	**2.7**	**2.9**	**5.4**	**1.3**	**4.10**

LSD= Least significant differences of means at ($p \leq 0.05$), CV = Coefficient of variation

4.6.2.2 Plant height

Plant height exhibited significant differences ($P\leq0.05$) for seasons (947.6*), locations (1298.2**) and genotypic variation (190.0***) among the $F_{2.3}$ families. Highly significant ($P\leq0.001$) interactions was observed for seasons x genotypes (83.2***), sites x genotypes (58.9***), season x site x genotype (30.0***) and seasons x sites (424.3*) among the $F_{2.3}$ families for plant height (Table 4.2). The $F_{2.3}$ families were taller during the long rain seasons with an average height of 98.2 and 94.2 cm for Mwea Research Station and Kirogo Experimental Farm compared with the short growing season across environments. Generally, the $F_{2.3}$ families at Mwea Research Station were taller with an average mean of 96.2 cm than at Kirogo Experimental Farm (90.6 cm). Plant height varied from 89.8 to 100.8 cm with the $F_{2.3}$ families of NERICA 13 x K 45 (100.8 cm) exhibiting the tallest plants while CG 14 x NERICA 10 (89.8 cm) followed by NERICA 4 x MWUR 4 (93.4 cm), NERICA 10 x KUCHUM (93.5 cm) and WAB-56-104 x NERICA 4 (94.9

cm) had short to intermediate plant height. The check variety Basmati 370 (128.3 cm) was the tallest among the $F_{2.3}$ families across sites (Table 4.3 and 4.5).

Table 4.5 Plant height (cm) of $F_{2.3}$ families grown at Mwea and Kirogo Farm during short rains of 2016 and long rains of 2017.

	Location/Season					
Genotype	**Mwea**			**Kirogo**		
	Long rain	Short rain	Mean	Long rain	Short rain	Mean
Basmati 370 (check)	129.7	126.7	128.7	128.3	125.0	127.7
WAB-56-104 (check)	103.3	99.0	101.2	98.7	97.3	98.0
KUCHUM (check)	99.0	99.3	99.2	91.3	84.7	88.0
MWUR 4 (check)	102.7	97.0	102.7	90.7	84.7	84.7
NERICA 1 (check)	93.3	89.0	93.3	89.3	82.3	82.3
NERICA 10 (check)	97.0	85.3	85.3	89.3	81.7	81.7
NERICA 4 (check)	96.0	93.3	96.0	94.3	88.7	88.7
NERICA10 x KUCHUM	98.0	95.3	96.7	97.0	83.7	90.3
NERICA13 x K45	111.7	99.0	105.3	103.3	83.0	96.2
NERICA4 x MWUR4	98.9	98.7	98.3	88.7	88.3	88.5
NERICA4 x NERICA1	102.7	96.7	99.7	97.7	86.3	92.0
MWUR4 x NERICA4	98.7	94.7	96.7	99.0	89.0	94.0
CG14 x NERICA10	89.0	87.3	88.2	95.0	88.0	91.5
WAB-56-104 x NERICA4	97.0	99.0	98.0	96.3	87.3	91.8
Grand mean	**98.2**	**94.3**	**96.2**	**94.2**	**86.6**	**90.6**
LSD 5 %	**4.71**	**2.57**	**3.69**	**5.95**	**2.45**	**4.65**
CV %	**2.9**	**1.6**	**2.3**	**3.7**	**1.7**	**3.1**

LSD= Least significant differences of means at ($p \leq 0.05$), CV = Coefficient of variation

4.6.2.3 Number of tillers plant^{-1}

There were no significant seasonal differences (154.3) for number of tillers but highly significant ($P \leq 0.001$) locational (3009.1***) and genotypic differences (72.9***) were observed for number of tillers. Highly significant ($P \leq 0.001$) interactions was observed for seasons x sites (265.0**) seasons x genotypes (18.3***), sites x genotypes (46.9***) and season x site x genotype (20.8***) for number of tillers plant^{-1} among the $F_{2.3}$ families (Table 4.2). The $F_{2.3}$ families at Kirogo Experimental Farm displayed the highest number of tillers plant^{-1} during the long (29.2) and short (24.6) growing seasons. Number of tillers varied from 15.7 to 25.5 at Mwea Research Station and from 25.2 to 33.5 at Kirogo Experimental Farm with the $F_{2.3}$ families of CG 14 x NERICA 10 (25.5) followed by WAB-56-104 x NERICA 4 (28.3) exhibited the highest number of tillers while NERICA 4 x NERICA 1 (21.5) had the least number of tillers. The $F_{2.3}$ families of WAB-56-104 x NERICA 4 (33.5) exhibited the highest numbers of tillers at Kirogo Experimental Farm compared to the check variety Basmati 370 (30.2) (Table 4.3 and 4.6).

Table 4.6 Number of tillers of $F_{2.3}$ families grown at Mwea and Kirogo Farm during short rains of 2016 and long rains of 2017.

	Location/Season					
Genotype	**Mwea**			**Kirogo**		
	Long rain	Short rain	Mean	Long rain	Short rain	Mean
Basmati 370 (check)	29.0	25.3	24.7	37.0	31.3	30.2
WAB-56-104 (check)	19.7	19.3	21.5	26.3	20.3	23.3
KUCHUM (check)	22.0	14.7	18.3	28.0	26.0	27.0
MWUR 4 (check)	21.3	18.0	21.3	23.0	18.3	18.3
NERICA 1 (check)	20.0	17.0	20.0	28.7	27.0	28.0
NERICA 10 (check)	13.0	11.3	11.3	31.3	21.0	21.0
NERICA 4 (check)	18.7	18.7	18.7	30.3	28.0	28.0
NERICA10 x KUCHUM	23.7	16.3	20.0	28.3	22.0	25.2
NERICA13 x K45	20.3	18.3	19.8	28.3	23.3	25.8
NERICA4 x MWUR4	16.3	15.7	16.0	32.3	21.3	26.8
NERICA4 x NERICA1	16.0	15.3	15.7	30.3	24.3	27.3
MWUR4 x NERICA4	18.7	15.7	17.2	29.3	23.0	26.2
CG14 x NERICA10	27.0	24.0	25.5	34.7	31.7	32.2
WAB-56-104 x NERICA4	22.3	16.8	18.2	31.3	33.7	33.5
Grand mean	**19.8**	**16.9**	**18.5**	**29.2**	**24.6**	**26.9**
LSD 5 %	**3.83**	**2.15**	**2.99**	**5.71**	**1.91**	**4.50**
CV %	**12.6**	**6.8**	**9.9**	**11.7**	**4.6**	**10.2**

LSD= Least significant differences of means at ($p \leq 0.05$), CV %= Coefficient of variation

4.6.2.4 Flag leaf length

Highly significant ($P \leq 0.001$) seasonal (366.1***), locational (1110.9***) and genotypic differences (20.2***) were observed for flag leaf length. Highly significant ($P \leq 0.001$) interactions was detected for seasons x genotypes (32.7***), sites x genotypes (15.8***), season x site x genotype (14.5***) and seasons x sites (25.9*) among the $F_{2.3}$ families for flag leaf length (Table 4.2). The $F_{2.3}$ families had longer flag leaf during the long rain seasons with an average of 31.7 for Mwea Research Station and 27.3 cm for Kirogo Experimental Farm. Comparing the two locations, rice plants at Mwea Research Station exhibited the longest flag leaf during the long (31.7 cm) and short (29.5 cm) growing seasons.

Flag leaf length varied between 29.8 and 32.3 cm at Mwea Research Station and between 22.3 and 27.5 cm at Kirogo Experimental Farm with NERICA 13 x K 45 (30.3 cm) followed by NERICA 10 x KUCHUM (28.8 cm) and WAB-56-104 x NERICA 4 (28.4 cm) exhibiting the longest flag leaves while MWUR 4 x NERICA 4 (27.3 cm) had the shortest flag leaf length. The check variety Basmati 370 (40.3 cm) recorded the longest flag leaves compared to all the $F_{2.3}$ families across sites (Table 4.3 and 4.7).

Table 4.7 Flag leaf length (cm) of $F_{2.3}$ families grown at Mwea and Kirogo Farm during short rains of 2016 and long rains of 2017.

	Location/Season					
Genotype	**Mwea**			**Kirogo**		
	Long rain	Short rain	Mean	Long rain	Short rain	Mean
Basmati 370 (check)	44.7	42.0	39.3	43.0	40.3	41.7
WAB-56-104 (check)	37.7	27.0	32.3	26.0	24.0	25.0
KUCHUM (check)	29.7	28.3	29.0	30.0	23.3	26.7
MWUR 4 (check)	32.0	28.3	28.3	26.0	20.3	20.3
NERICA 1 (check)	28.0	27.3	27.3	26.3	25.7	25.7
NERICA 10 (check)	34.7	29.0	29.0	30.3	23.7	23.7
NERICA 4 (check)	30.7	29.0	29.0	30.0	24.3	24.3
NERICA10 x KUCHUM	27.0	37.0	32.0	26.0	25.0	25.5
NERICA13 x K45	35.0	31.0	33.0	31.3	23.7	27.5
NERICA4 x MWUR4	29.0	31.3	30.2	25.7	28.0	26.8
NERICA4 x NERICA1	32.3	32.3	32.3	24.0	20.7	22.3
MWUR4 x NERICA4	33.3	28.0	30.7	25.7	22.0	23.8
CG14 x NERICA10	33.0	31.7	32.3	28.7	25.0	26.8
WAB-56-104 x NERICA4	32.7	27.0	29.8	28.7	21.3	25.0
Grand mean	**31.7**	**29.5**	**30.6**	**27.3**	**23.6**	**25.5**
LSD 5 %	**3.59**	**2.26**	**2.89**	**2.95**	**1.68**	**2.32**
CV %	**6.8**	**4.6**	**5.8**	**6.4**	**4.2**	**5.6**

LSD= Least significant differences of means at ($p \leq 0.05$), CV = Coefficient of variation

4.6.2.5 Panicle length

There were significant ($P \leq 0.05$) seasonal (17.4*) and locational (80.1**) differences for panicle length but no significant genotypic differences (1.3) were observed for the same trait. Highly significant ($P \leq 0.001$) interactions were detected for seasons x sites (6.1**), seasons x genotype (3.4***), sites x genotypes (3.8***) and season x site x genotype (1.9**) among the $F_{2.3}$ families for panicle length (Table 4.2). The $F_{2.3}$ families exhibited longer panicle during the long rain seasons with an average of 22.6 and 21.1 cm for Mwea Research Station and Kirogo Experimental Farm respectively. Compared to Kirogo Experimental Farm, the $F_{2.3}$ families at Mwea Research Station generally exhibited longer panicles with an average mean of 22.0 cm. Panicle length varied from 21.8 to 22.8 cm at Mwea Research Station and from 19.8 to 20.8 cm at Kirogo Experimental Farm. The $F_{2.3}$ families of NERICA 10 x KUCHUM (21.7 cm) exhibited the longest panicle while NERICA 4 x NERICA 1 (21.0 cm) had the shortest panicle. Compared to the $F_{2.3}$ families, the check Basmati 370 (28.2 cm) had the longest panicle across sites (Table 4.3 and 4.8).

Table 4.8 Panicle length (cm) of $F_{2.3}$ families grown at Mwea and Kirogo Farm during short rains of 2016 and long rains of 2017.

	Location/Season					
Genotype	**Mwea**			**Kirogo**		
	Long rain	Short rain	Mean	Long rain	Short rain	Mean
Basmati 370 (check)	28.0	27.0	26.0	26.3	25.7	24.0
WAB-56-104 (check)	22.7	21.3	22.0	20.3	20.3	20.3
KUCHUM (check)	22.0	18.0	20.0	22.3	21.3	21.8
MWUR 4 (check)	23.3	22.0	22.0	20.7	20.3	20.3
NERICA 1 (check)	22.7	21.0	22.7	20.3	20.3	20.3
NERICA 10 (check)	23.7	22.3	22.3	21.7	20.7	20.7
NERICA 4 (check)	22.7	21.3	22.7	21.3	21.0	21.0
NERICA10 x KUCHUM	22.7	22.3	22.0	21.3	20.3	20.8
NERICA13 x K45	23.0	20.7	21.8	22.0	19.0	20.5
NERICA4 x MWUR4	22.3	22.0	22.2	21.0	20.0	20.5
NERICA4 x NERICA1	23.0	21.3	22.3	20.7	19.0	19.8
MWUR4 x NERICA4	23.3	22.3	22.8	21.3	19.0	20.2
CG14 x NERICA10	22.7	21.7	22.4	20.3	20.3	20.3
WAB-56-104 x NERICA4	22.0	22.0	22.0	21.3	19.3	20.3
Grand mean	**22.6**	**21.4**	**22.0**	**21.1**	**20.1**	**20.6**
LSD 5 %	**1.53**	**1.29**	**1.37**	**1.65**	**0.97**	**1.31**
CV %	**4.1**	**3.5**	**3.8**	**4.6**	**2.9**	**3.9**

LSD= Least significant differences of means at ($p \leq 0.05$), CV = Coefficient of variation

4.6.2.6 Number of panicles plant^{-1}

There were no significant seasonal differences for number of panicles (14.9) but highly significant ($P \leq 0.001$) locational (4041.5**) and genotypic differences (109.2***) were observed for the same trait. Significant interactions ($P \leq 0.05$) were observed for seasons x sites (126.9*), seasons x genotypes (41.5***), sites x genotypes (45.4***) and season x site x genotype (9.8*) among the $F_{2.3}$ families for number of panicles plant^{-1} (Table 4.2). The long rain season had the highest number of effective tillers for both Mwea Research Station (17.7) and Kirogo Experimental Farm (27.7) respectively. Number of panicles plant^{-1} was high at Kirogo Experimental Farm (26.2) compared to Mwea Research Station (16.4) across the two growing seasons. Number of panicles plant^{-1} varied from 13.8 to 21.2 at Mwea Research Station and from 23.7 to 34.5 at Kirogo Experimental Farm. The $F_{2.3}$ families of WAB-56-104 x NERICA 4 (27.8) exhibited the highest number of effective tillers while MWUR 4 x NERICA 4 (18.8) had the lowest number of effective tillers across environments. Compared to the $F_{2.3}$ families, the check Basmati 370 (36.3) had the highest number of panicles plant^{-1} across sites (Table 4.3 and 4.9).

Table 4.9 Number of panicles of $F_{2.3}$ families grown at Mwea and Kirogo Farm during short rains of 2016 and long rains of 2017.

	Location/Season					
Genotype	**Mwea**			**Kirogo**		
	Long rain	Short rain	Mean	Long rain	Short rain	Mean
Basmati 370 (check)	29.7	25.0	24.8	37.7	36.3	33.5
WAB-56-104 (check)	19.0	18.0	18.5	25.3	19.7	22.5
KUCHUM (check)	18.7	15.0	16.8	25.0	20.0	22.5
MWUR 4 (check)	17.3	13.3	17.3	21.7	18.7	18.7
NERICA 1 (check)	18.0	15.3	18.0	26.0	24.7	26.0
NERICA 10 (check)	12.0	10.3	10.3	29.7	19.7	19.7
NERICA 4 (check)	18.0	16.0	18.0	28.7	27.0	27.0
NERICA10 x KUCHUM	17.6	15.6	16.7	27.7	23.7	25.7
NERICA13 x K45	21.0	15.7	18.3	29.3	26.0	28.2
NERICA4 x MWUR4	15.0	14.2	14.7	30.0	27.7	28.8
NERICA4 x NERICA1	14.0	13.7	13.8	29.0	27.7	28.3
MWUR4 x NERICA4	14.9	14.0	14.0	27.7	19.7	23.7
CG14 x NERICA10	22.0	20.3	21.2	35.0	31.5	33.8
WAB-56-104 x NERICA4	23.0	15.8	19.2	29.7	39.3	34.5
Grand mean	**17.6**	**15.2**	**16.4**	**27.7**	**24.5**	**26.2**
LSD 5 %	**4.11**	**2.0**	**3.12**	**5.35**	**1.91**	**4.00**
CV %	**15.5**	**7.0**	**11.6**	**11.6**	**4.5**	**9.3**

LSD= Least significant differences of means at ($p \leq 0.05$), CV = Coefficient of variation

4.6.2.7 Number of filled grains panicle^{-1}

There were significant (P≤0.05) seasonal (3886.1*), locational (2672***) and genotypic differences (960.4***) for filled grains. Significant interactions (P≤0.05) were observed for seasons x sites (1141.9*). Highly significant (P≤0.001) interactions were detected for seasons x genotypes (506.1***), sites x genotypes (406.3***) and season x site x genotype (712.5***) among the $F_{2.3}$ families for filled grains panicle^{-1} (Table 4.2). Generally, the $F_{2.3}$ families at Kirogo Experimental Farm (123.0) had higher fertile grains panicle^{-1} than at Mwea Research Station (115.1). Filled grains panicle^{-1} varied from 99.8 to 125.5 at Mwea Research Station and 105.3 to 138.3 at Kirogo Experimental Farm. The $F_{2.3}$ families of MWUR 4 x NERICA 4 (129.9), WAB-56-104 x NERICA 4 (128.8) had high number of fertile grains panicle^{-1} while NERICA 13 x K 45 (107.5) had the lowest. The check variety Basmati 370 had higher filled grains panicle^{-1} compared to all the $F_{2.3}$ families studied (Table 4.3 and 4.10).

Table 4.10 Number of filled grains of $F_{2.3}$ families grown at Mwea and Kirogo Farm during short rains of 2016 and long rains of 2017.

	Location/Season					
Genotype	**Mwea**			**Kirogo**		
	Long rain	Short rain	Mean	Long rain	Short rain	Mean
Basmati 370 (check)	138.3	121.7	119.5	137.3	120.3	121.8
WAB-56-104 (check)	151.0	92.3	121.7	135.7	138.3	137.0
KUCHUM (check)	121.0	113.3	117.2	118.0	110.3	114.2
MWUR 4 (check)	123.3	121.3	121.3	126.3	109.7	109.7
NERICA 1 (check)	109.0	120.0	120.0	112.7	90.3	90.3
NERICA 10 (check)	115.3	110.7	110.7	115.0	104.0	104.0
NERICA 4 (check)	126.3	128.0	128.0	132.7	135.0	135.0
NERICA10 x KUCHUM	106.7	107.0	106.8	122.7	88.0	105.3
NERICA13 x K45	130.3	116.0	123.2	125.0	138.7	131.8
NERICA4 x MWUR4	117.0	82.7	99.8	123.0	116.7	119.8
NERICA4 x NERICA1	127.3	82.0	104.7	122.0	141.3	131.7
MWUR4 x NERICA4	128.7	122.3	125.5	126.7	150.0	138.3
CG14 x NERICA10	116.0	107.7	111.8	124.0	143.7	133.8
WAB-56-104 x NERICA4	120.3	115.0	117.7	132.3	131.3	131.8
Grand mean	**122.5**	**107.6**	**115.1**	**125.2**	**120.8**	**123.0**
LSD 5 %	**21.7**	**11.5**	**17.5**	**24.8**	**3.5**	**17.3**
CV %	**10.6**	**6.4**	**9.3**	**11.8**	**1.7**	**8.6**

LSD= Least significant differences of means at (p ≤ 0.05), CV = Coefficient of variation

4.6.2.8 Grain yield

Significant ($P \leq 0.05$) seasonal (714*), locational (3045**) and genotypic differences (2099**) were observed for grain yield. Significant ($P \leq 0.05$) interactions were noted for seasons x genotypes (700*), sites x genotypes (377***) and season x site x genotype (620*) among the $F_{2.3}$ families for grain yield (Table 4.2). The $F_{2.3}$ families had high yields at both Mwea Research Station (5,630 kg $ha^{-1)}$ and Kirogo Experimental Farm (6,370 kg ha^{-1}) during the long rain seasons. Generally, the $F_{2.3}$ families had better yields at Kirogo Experimental Farm with an average mean of 5,051 kg ha^{-1} compared to 4,700 kg ha^{-1} at Mwea Research Station. Grain yield varied from 3,556 to 7,349 kg ha^{-1} at Mwea Research Station and from 3,493 to 8,527 kg ha^{-1} at Kirogo Experimental Farm. Highest grain yield was observed in the $F_{2.3}$ families of WAB-56-104 x NERICA 4 (9,350 kg ha^{-1}), while NERICA 13 x K45 (3,080 kg ha^{-1}) was the lowest grain yielder. The $F_{2.3}$ families of WAB-56-104 x NERICA 4 were good grain yielders compared to the check variety Basmati 370 (4,030 kg ha^{-1}) across sites (Table 4.3 and 4.11).

Table 4.11 Grain yield (kg ha^{-1}) of $F_{2.3}$ families grown at Mwea and Kirogo Farm during short rains of 2016 and long rains of 2017.

	Location/Season					
Genotype	**Mwea**			**Kirogo**		
	Long rain	Short rain	Mean	Long rain	Short rain	Mean
Basmati 370 (check)	4,470	4,030	4,020	4,920	4,180	4,099
WAB-56-104 (check)	7,930	6,540	5,567	7,400	7,380	5,893
KUCHUM (check)	5,740	4,630	4,487	5,710	5,690	4,536
MWUR 4 (check)	5,400	4,240	3,062	6,040	5,860	3,710
NERICA 1 (check)	4,020	4,170	3,689	5,690	5,350	5,352
NERICA 10 (check)	3,040	3,220	3,225	4,790	4,220	4,770
NERICA 4 (check)	5,660	5,320	4,990	5,610	5,140	4,471
NERICA10 x KUCHUM	5,620	4,400	5,006	5,420	5,180	5,203
NERICA13 x K45	3,790	3,330	3,556	7,530	5,330	4,761
NERICA4 x MWUR4	6,680	5,590	5,468	6,370	5,540	5,624
NERICA4 x NERICA1	4,560	3,940	4,232	7,430	7,160	6,127
MWUR4 x NERICA4	5,050	4,880	4,966	5,220	4,980	4,750
CG14 x NERICA10	5,480	4,110	4,128	7,290	6,030	3,493
WAB-56-104 x NERICA4	8,030	7,600	7,349	9,100	8,920	8,527
Grand mean	**5,630**	**4,850**	**4,700**	**6,370**	**5,800**	**5,051**
LSD 5 %	**1080**	**814**	**1,097**	**1042**	**751**	**1,251.4**
CV %	**12.8**	**8.7**	**14.0**	**10.5**	**7.1**	**13.6**

LSD= Least significant differences of means at ($p \leq 0.05$), CV = Coefficient of variation

4.6.2.9 1000-grain mass

Highly significant ($P \leq 0.001$) seasonal (116.2**) and genotypic differences (8.2***) were observed for 1000 grain mass and no significant locational differences (0.1). Significant ($P \leq 0.05$) interactions were for seasons x sites (7.9*) and sites x genotypes (2.6***) were detected while no significant interaction for seasons x genotypes (1.6) and season x site x genotype (0.8) among the $F_{2.3}$ families for 1000 grain mass (Table 4.2). The $F_{2.3}$ families exhibited heaviest 1000-grain mass at Mwea Research Station (24.5 g) and Kirogo Experimental Farm (24.1 g) during the long growing season than the short rain season. 1000-grain mass varied between 22.9 to 24.6 g at Mwea Research Station and between 22.9 to 25.1 g at Kirogo Experimental Farm. The $F_{2.3}$ families of WAB-56-104 x NERICA 4 (24.9 g) exhibited the heaviest 1000 grain mass, while NERICA 13 x K 45 (22.9 g) had the lightest grains (Table 4.3 and 4.12).

Table 4.12 1000-grain mass (g) of $F_{2.3}$ families grown at Mwea and Kirogo Farm during short rains of 2016 and long rains of 2017.

	Location/Season					
Genotype	**Mwea**			**Kirogo**		
	Long rain	Short rain	Mean	Long rain	Short rain	Mean
Basmati 370 (check)	25.9	24.9	22.4	26.8	25.7	23.3
WAB-56-104 (check)	23.4	22.9	23.2	23.5	22.6	23.1
KUCHUM (check)	23.9	21.8	22.8	23.1	21.9	22.5
MWUR 4 (check)	24.9	22.0	22.0	24.5	23.2	23.2
NERICA 1 (check)	26.2	24.2	24.2	24.9	24.9	24.9
NERICA 10 (check)	23.1	20.4	20.4	22.6	20.6	20.6
NERICA 4 (check)	22.6	23.0	23.0	23.1	22.2	22.2
NERICA10 x KUCHUM	25.4	22.6	23.9	23.8	22.7	23.2
NERICA13 x K45	24.9	21.7	23.3	25.4	23.6	24.5
NERICA4 x MWUR4	26.0	22.1	24.1	23.8	22.1	22.9
NERICA4 x NERICA1	25.2	23.6	24.4	23.8	22.3	23.0
MWUR4 x NERICA4	24.9	22.6	23.7	25.2	24.9	25.1
CG14 x NERICA10	24.3	21.6	22.9	25.3	23.5	24.3
WAB-56-104 x NERICA4	25.5	23.6	24.6	24.2	22.7	23.4
Grand mean	**24.5**	**22.4**	**23.5**	**24.1**	**22.8**	**23.5**
LSD 5 %	**1.06**	**2.15**	**1.64**	**1.34**	**2.03**	**1.66**
CV %	**2.6**	**5.7**	**4.3**	**3.3**	**5.3**	**4.3**

LSD= Least significant differences of means at ($p \leq 0.05$), CV = Coefficient of variation

4.6.2.10 Correlation analysis of agronomic and yield traits in $F_{2.3}$ families

The association between agronomic and yield traits was determined using the data collected at Mwea Research Station and Kirogo Experimental Farm. The results of correlation analysis are presented in Table 4.13. (r = correlation coefficient and it ranges from 0 to 1). The correlation analysis showed that grain yield was positively correlated with numbers of tillers plant^{-1} (r = 0.35**), number of effective tillers plant^{-1} (r = 0.51**) and number of fertile grains panicle^{-1} (r = 0.39**). However, grain yield was negatively correlated with plant height (r = -0.29*), panicle length (r = -0.36**), days to 50 % flowering (r = -0.24*), days to maturity (r = -0.24*) and flag leaf length (r = -0.38**). Panicle length showed positive and significant association with 1000-grain mass (r = 0.26*), flag leaf length (r = 0.72**) and plant height (r = 0.62**) and exhibited a negative correlation with fertile grains panicle^{-1} (r = -0.23*), number of effective tillers (r = -0.55**) and number of tillers plant^{-1} (r = -0.38**). Plant height had a strong correlation with 1000-grain mass (r = 0.38**), days to 50 % flowering (r = 0.50**) and flag leaf length (r = 0.56**) while it exhibited a negative association with number of effective tillers plant^{-1} (r = -0.39**) and number of tillers plant^{-1} (r = -0.24*). Number of tillers plant^{-1} strong correlation with days to 50 % flowering (r = 0.24*), days to maturity (r = 0.32*), fertile grains panicle^{-1} (r = 0.36**) and number of effective tillers plant^{-1} (r = 0.89**) and negatively associated with flag leaf length (r = -0.41**). Number of spikelets panicle^{-1} was positively correlated with fertile grains panicle^{-1} (r = 0.27*). Number of effective tillers plant^{-1} exhibited a positive correlation with days to maturity (r = 0.23*) and fertile grains panicle^{-1} (r = 0.37**) and negatively associated with flag leaf length (r = -0.57**). Flag leaf length was positively correlated with days to 50 % flowering (r = 0.22*) and negatively correlated with fertile grains panicle^{-1} (r = -0.34). Fertile grains panicle^{-1} was positively associated with 1000-grain mass (r = 0.24*) and days to maturity (r = 0.25*). Days to maturity was positively correlated with days to 50 % flowering (r = 0.67**).

Table 4.13 Correlations between agronomic and yield traits among $F_{2.3}$ families.

	1000 grain mass (g)	50% Days to flowering (days)	Days to maturity (days)	Filled grains panicle^{-1}	Flag leaf length (cm)	Grain yield (kg ha^{-1})	Number of panicles plant^{-1}	Number of spikelets panicle^{-1}	Number of tillers plant^{-1}	Plant height (cm)
50% Days to flowering (d)	0.12	-								
Days to maturity (d)	0.01	0.67**	-							
Filled grains panicle^{-1}	0.24*	0.12	0.25*	-						
Flag leaf length (cm)	0.09	0.22*	0.06	-0.34*	-					
Grain yield (kg ha^{-1})	-0.13	-0.24*	-0.24*	0.39*	-0.38**	-				
Number of panicles plant	-0.17	0.07	0.23*	0.37**	-0.57**	0.51**	-			
Spikelets panicle^{-1}	-0.14	0.17	0.01	0.27*	-0.12	0.16	0.09	-		
Number of tillers plant^{-1}	-0.04	0.24*	0.32*	0.36**	-0.41**	0.35**	0.89**	0.01	-	
Plant height (cm)	0.38**	0.49**	0.18	-0.04	0.56**	-0.29*	-0.39**	0.13	-0.24*	-
Panicle length (cm)	0.26*	0.15	-0.09	-0.23*	0.72**	-0.36**	-0.55**	-0.02	-0.38**	0.62**

* Significant correlation at 5 % level of probability, ** Significant correlation at 1 % level of probability

4.7 GRAIN QUALITY ATTRIBUTES

4.7.1 Grain length

The results for analysis of grain length are presented in Table 4.14. The grain length of the $F_{2.3}$ families varied from 6.84 to 7.06 mm with a mean value of 6.93 mm. Maximum grain length was recorded in MWUR 4 x NERICA 4 (7.06 mm) while NERICA 4 x MWUR 4 (6.69 mm) exhibited the least grain length. The check variety Basmati 370 (7.80 cm) recorded a very long grain length compared to all the tested $F_{2.3}$ families (Fig 4.5).

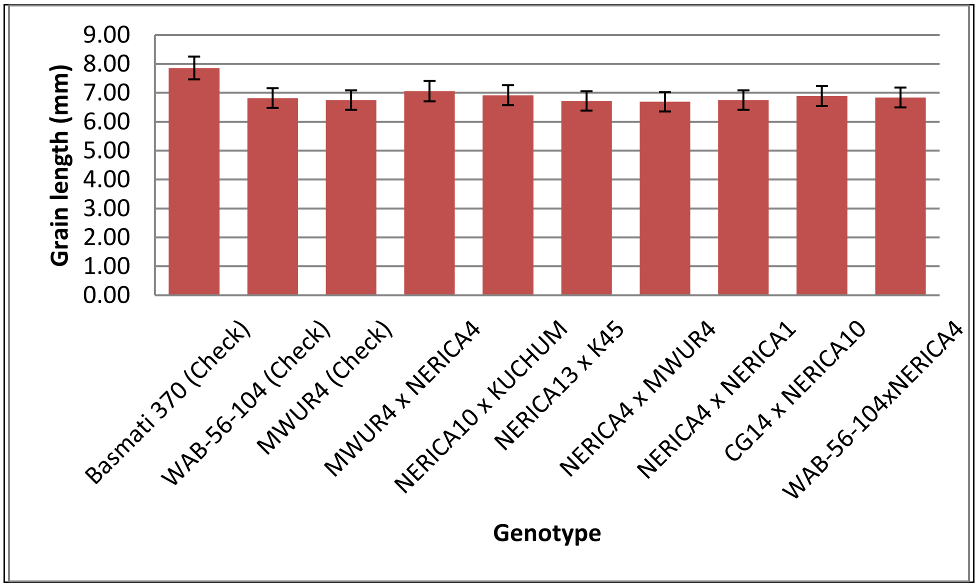


Figure 4.5 Distribution of grain length in $F_{2.3}$ families and checks

4.7.2 Grain width

The results for analysis of grain width are presented in Table 4.14. The grain width among the $F_{2.3}$ families varied from 2.10 to 2.68 mm with a mean value of 2.43 mm. The $F_{2.3}$ families of MWUR 4 x NERICA 4 (2.68 mm), followed by NERICA 13 x K45 (2.65 mm) exhibited high grain width while NERICA 4 x MWUR 4 (2.10 mm) had the lowest grain width among the $F_{2.3}$ families. The check Basmati 370 (2.67) had relatively higher grain width (Fig 4.6).

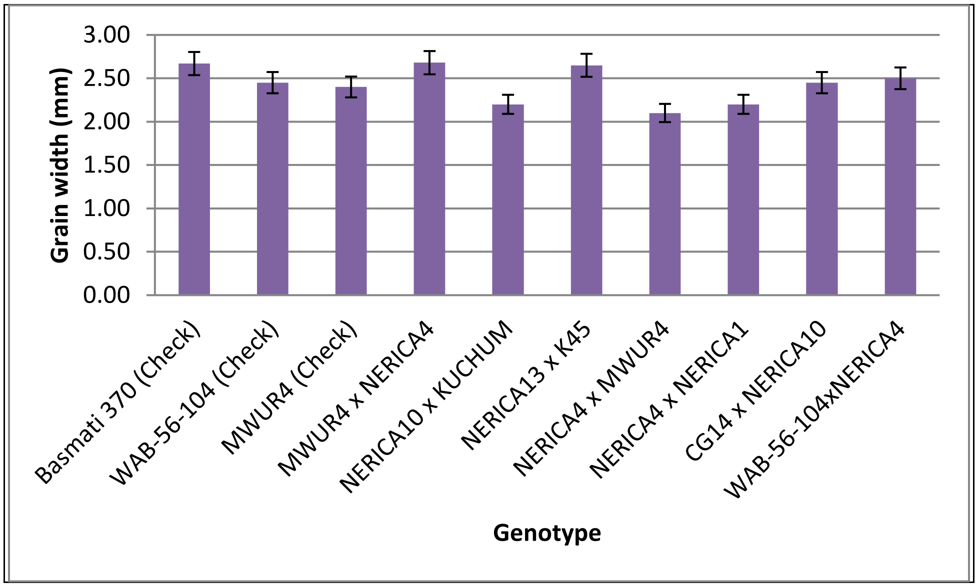


Figure 4.6 Distribution of grain width in $F_{2.3}$ families and checks

4.7.3 Length to width ratio

The results for analysis of length to width ratio (L/W) are presented in Table 4.14. The L/W ratio among the $F_{2.3}$ families varied from 2.54 to 3.19 with a mean value of 2.94. The $F_{2.3}$ families of NERICA 4 x MWUR 4 (3.19) followed by NERICA 10 x KUCHUM (3.15) and NERICA 4 x NERICA 1 (3.07) exhibited high L/W ratio while NERICA 13 x K45 (2.54) had the lowest L/W ratio among the $F_{2.3}$ families. The check variety Basmati 370 (3.32) exhibited the highest L/W ratio among the tested genotypes (Fig 4.7).

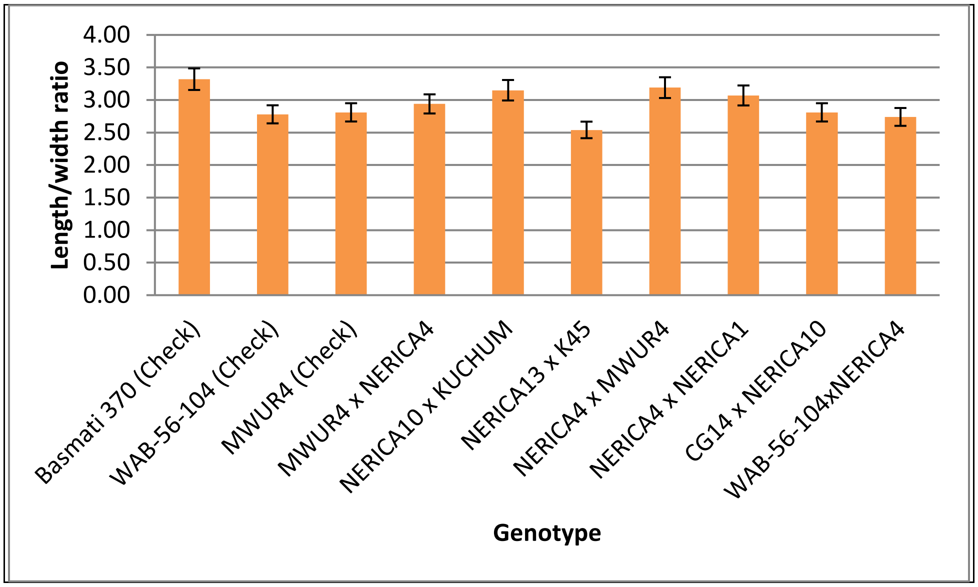


Figure 4.7 Distribution of L/W ratio in $F_{2.3}$ families and checks

4.7.4 Aroma

The results of sensory analysis are presented in Table 4.14. The sensory test showed that the $F_{2.3}$ families of MWUR 4 x NERICA 4, NERICA 4 x MWUR 4, CG 14 x NERICA 10 and WAB-56-104 x NERICA 4 were slightly aromatic while NERICA 10 x KUCHUM, NERICA 13 x K45 and NERICA 4 x NERICA 1 were non-aromatic. The check Basmati 370 had strong aroma compared to all the $F_{2.3}$ families evaluated (Table 4.8).

Figure 4.8 Test panel assessing aroma in rice samples

4.7.5 Cooking time

The analysis of culinary qualities of $F_{2.3}$ families is presented in Table 4.14. The $F_{2.3}$ families of NERICA 13 x K45 (45.33 minutes) followed by NERICA 10 x KUCHUM (43.33 minutes) took longer time to cook while NERICA 4 x NERICA 1 (22.33 minutes) followed by MWUR 4 x NERICA 4 (23.33 minutes) had the least time to cooking. The check Basmati 370 had moderate cooking time (23.67 minutes) (Fig 4.9).

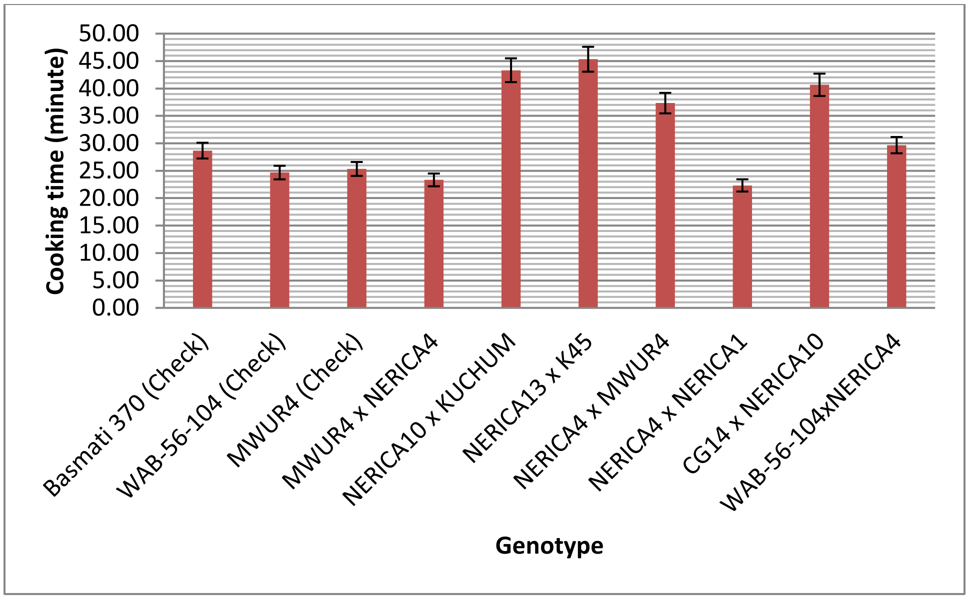


Figure 4.9 Variation of cooking time among $F_{2.3}$ families and checks

4.7.6 Alkali spreading value

The alkali digestion of the rice kernels varied from 2 to 7 among the genotypes indicating a wide range of gelatinization temperature. The $F_{2.3}$ families of NERICA 4 x NERICA 1, MWUR 4 x NERICA 4 had alkali digestion scale 6 while WAB-56-104 x NERICA 4 had scale 7 but NERICA 10 x KUCHUM exhibited scale 4. The $F_{2.3}$ families of NERICA 4 x MWUR 4 showed scale 2 while NERICA 13 x K45 and CG 14 x NERICA 10 had scale 3. The check variety Basmati 370 exhibited scale 4.

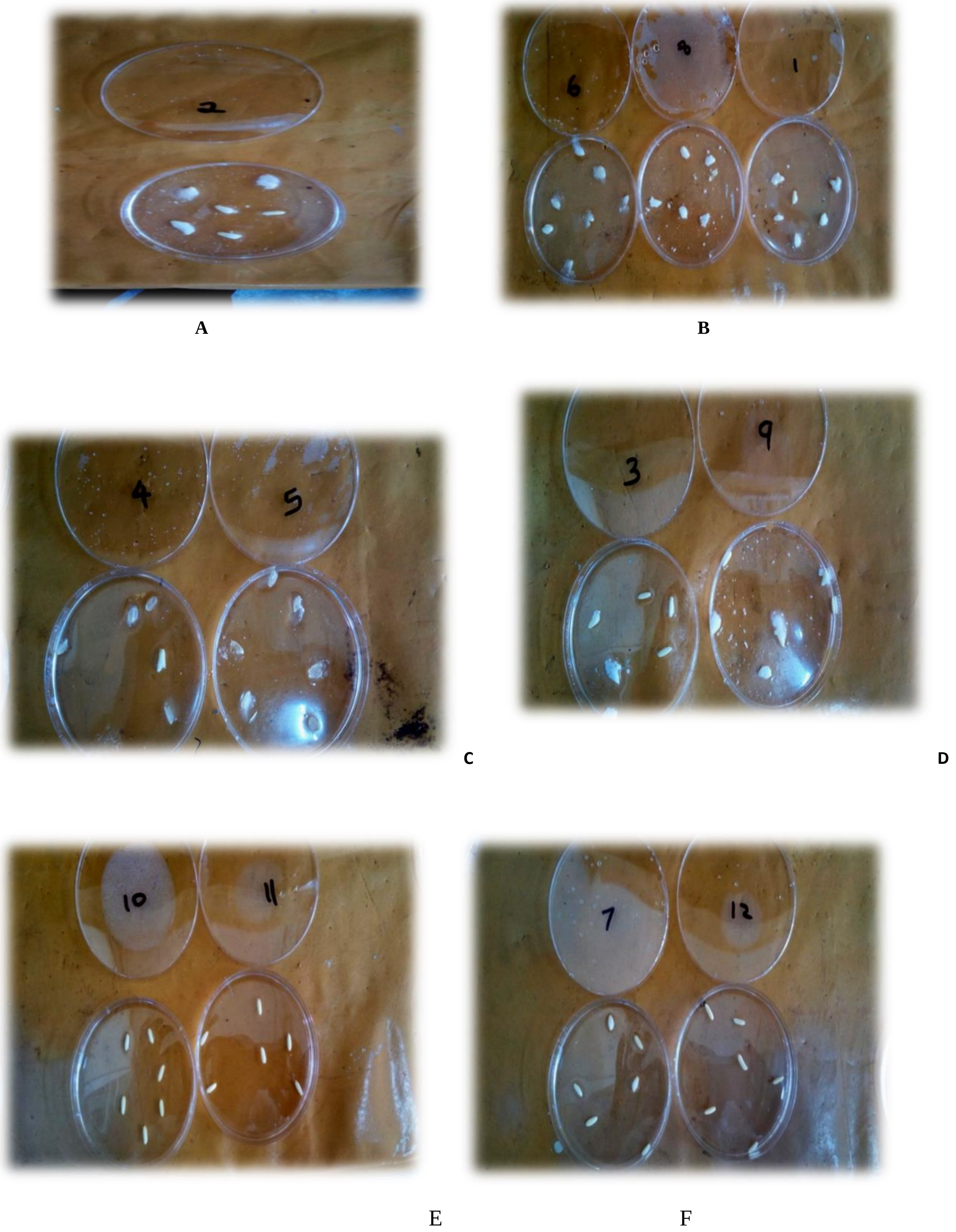


Figure 4.10 Alkali spreading scale; A-scale 5, B-scale 6, C-scale 7, D-scale 4, E- scale 2 and F-scale 3.

4.7.7 Gelatinization temperature

The results of gelatinization temperature are presented in Table 4.14. The gelatinization temperature of starch for the rice kernels varied from low to high (57ºC to 79ºC). The highest gelatinization temperature was recorded in the $F_{2.3}$ families of NERICA 13 x K45 (79ºC) while NERICA 4 x NERICA 1 (57ºC) followed by MWUR 4 x NERICA 4 (58.67ºC) had the lowest gelatinization temperatures. The check variety Basmati 370 had a moderate (70ºC) gelatinization temperature.

4.7.8 Gel consistency

The analysis of gel consistency among the $F_{2.3}$ families is presented in Table 4.14. Gel consistency varied from 45 to 65 mm. The $F_{2.3}$ families of WAB-56-104 x NERICA 4 (65 mm) followed by NERICA 4 x NERICA 1 (63 mm) and MWUR 4 x NERICA 4 (63 mm) exhibited the highest gel consistency while NERICA 13 x K45 (45 mm) had the least value of gel consistency. The check variety Basmati 370 exhibited a hard gel of 40 mm.

Table 4.14 Grain quality traits of $F_{2.3}$ families grown at Mwea Research Station during 2016 cropping season.

Genotype	Grain length (mm)	Grain width (mm)	Length/width ratio	Grain shape category	Grain length category	Aroma test
Basmati 370 (check)	7.86	2.67	3.32	Slender	Very long	Strong
WAB-56-104 (check)	6.82	2.45	2.78	Medium	Long	No
MWUR 4 (check)	6.75	2.40	2.81	Medium	Long	No
MWUR 4 x NERICA 4	7.06	2.68	2.94	Medium	Long	Slight
NERICA10 x KUCHUM	6.92	2.20	3.15	Slender	Long	No
NERICA13 x K45	6.72	2.65	2.54	Medium	Long	No
NERICA 4 x MWUR 4	6.69	2.10	3.19	Slender	Long	Slight
NERICA 4 x NERICA 1	6.75	2.20	3.07	Slender	Long	No
CG14 x NERICA10	6.89	2.45	2.81	Medium	Long	Slight
WAB-56-104 x NERICA 4	6.84	2.50	2.74	Medium	Long	Slight
Grand Mean	**6.93**	**2.43**	**2.94**	**-**	**-**	**-**
CV %	**2.1**	**0.10**	**0.13**	**-**	**-**	**-**
LSD 5 %	**0.02**	**0.03**	**0.06**	**-**	**-**	**-**

LSD = Least significant differences of means at ($p \leq 0.05$), CV = Coefficient of variation

Table 4.14 continued

Genotype	Cooking time (minutes)	Alkali spreading value	Gelatinization Temperature (^{0}C)	Temperature category	Gel Consistency (mm)	Gel category
Basmati 370 (check)	23.67	4	70.00	Intermediate	40	Hard gel
WAB-56-104 (check)	24.67	6	65.00	Low	65	Soft gel
MWUR 4 (check)	25.33	6	55.00	Low	64	Soft gel
MWUR 4 x NERICA 4	23.33	6	58.67	Low	63	Soft gel
NERICA 10 x KUCHUM	43.33	2	75.00	High	53	Medium
NERICA 13 x K45	45.33	3	79.00	High	45	Medium
NERICA 4 x MWUR 4	37.33	2	76.00	High	48	Medium
NERICA 4 x NERICA 1	22.33	6	57.00	Low	63	Soft gel
CG 14 x NERICA 10	40.67	3	78.00	High	60	Medium
WAB-56-104 x NERICA 4	22.67	7	69.00	Low	65	Soft gel
Grand Mean	**39.47**	**4.3**	**67.87**	**-**	**60.6**	**-**
CV %	**0.94**	**0**	**0.10**	**-**	**0**	**-**
LSD 5 %	**1.9**	**0**	**0.31**	**-**	**0**	**-**

LSD = Least significant differences of means at ($p \leq 0.05$), CV = Coefficient of variation

4.7.9 Correlations between physico-chemical characters

There were significant ($P \leq 0.05$) correlations among the physico-chemical characters (Table 4.15). Alkali spreading value (ASV) was negatively correlated with gelatinization temperature (r = -0.67**). Length to breadth ratio showed a positive and significant correlation with grain length (r = 0.55*) and negatively correlated with grain width (r = -0.38*). Cooking time was strongly correlated with gelatinization temperature (r = 0.36**) and gel consistency (r = 0.58**) but negatively correlated with grain length (r = -0.69**). Gel consistency was negatively correlated with grain length (r = -0.61**) and grain width (r = -0.69**). However, grain length was strongly correlated with grain width (r = 0.51*).

Table 4.15 Correlations between physico-chemical characteristics of rice grain.

	Alkali spreading value	Length to width ratio	Cooking time (minutes)	Gel consistency (mm)	Gelatinization temperature (^{0}C)	Grain length (mm)
Length to width ratio	-0.06	-				
Cooking time (mins)	0.13	-0.34	-			
Gel consistency (mm)	0.13	0.06	0.58**	-		
Gelatinization temperature (^{0}C)	-0.67**	-0.07	0.36**	-0.27	-	
Grain length (mm)	0.04	0.55*	-0.69**	-0.61**	0.02	-
Grain width (mm)	0.17	-0.38*	-0.35	-0.69**	0.004	0.51*

Significant correlation at 5 % level of probability, ** Significant correlation at 1 % level of probability

4.8 DISCUSSION

4.8.1 Agronomic performance of $F_{2.3}$ families across environments

4.8.1.2 Duration to 50 % flowering and days to maturity

The $F_{2.3}$ families at Kirogo Experimental Farm took relatively short duration to reach 50 % flowering compared to Mwea Research Station. The $F_{2.3}$ families of WAB-56-104 x NERICA 4 NERICA 4 x NERICA 1, NERICA 10 x KUCHUM and NERICA 4 x MWUR 4 flowered early while NERICA 13 x K 45 took longer days to reach 50 % flowering across environments. The difference in response to flowering among the genotypes in the varying environments could be due to the warm weather at Kirogo Experimental Farm (Fig. 4.3). Delayed flowering at Mwea Research Station could be due to water stress (Fig. 4.2) that affected the important biochemical processes in the rice plants. Insufficient soil moisture negatively affect plant physiological processes such as transpiration, photosynthesis, respiration as well as translocation of assimilates to the actively growing regions of the plant (Turner, 1986; Tamu, 2015). Water stress delays the phenological development of the rice plant in terms of flowering and maturity. Late flowering leads to delay in plant maturity. The unreliability and variation in rainfall distribution during the long and the short rain seasons (Fig. 4.2) could be the reason for the delay in 50 % flowering and maturity of the $F_{2.3}$ families. Sabouri and Nahvi (2009) reported that 50 % days to flowering and days to maturity were controlled by both genetic and environmental factors. Therefore, $F_{2.3}$ families of WAB-56-104 x NERICA 4 and NERICA 10 x KUCHUM could be selected for growing in areas with marginal rainfall patterns due to the relatively short duration to maturity. The short duration genotypes can be used as parents by the breeder to develop early maturing genotypes (Jamal et al., 2009).

4.8.1.3 Plant height

Generally, the $F_{2.3}$ families at Mwea Research Station were taller than at Kirogo Experimental Farm. The $F_{2.3}$ families of NERICA 13 x K 45 had the tallest plants while CG 14 x NERICA 10, NERICA 4 x MWUR 4, NERICA 10 x KUCHUM and WAB-56-104 x NERICA 4 had short to intermediate plant height. The variation in plant height at the two locations could be due to the supplemental irrigation and ambient temperature at Mwea Research Station (Fig. 4.3) during the crop growing period that probably stimulated vegetative growth due to accumulation of assimilates in the stems resulting to increase in plant height.

The results further revealed that rice plants with relatively short to intermediate height observed at Kirogo Experimental Farm exhibited higher grain yields than the rice plants at Mwea Research Station. This could be due to the favourable growing conditions at Kirogo Experimental Farm characterized by good soils with high water retention capacity and high humidity (Fig. 4.4). Hussain et al., (2005) reported that transplanting time, sowing method, water and soil condition affect plant height in rice plants. Rice plants with short to intermediate height generally have high grain yields. This could be attributed to the supply of assimilates to the developing grains. Tall rice plants like NERICA 13 x K45 recorded low grain yields. This may be due utilization of assimilates in vegetative growth rather than being imported for seed formation and grain filling. Yoshida (1981) reported that high grain yield in rice varieties with short plant height was associated with increase in lodging resistance of the rice plant. Therefore, selection of short to intermediate plant type would be advantageous in relation to grain yield.

4.8.1.4 Number of tillers plant^{-1}

The $F_{2.3}$ families at Kirogo Experimental Farm displayed the highest number of tillers plant^{-1} compared to Mwea Research Station during the long and short growing seasons. The $F_{2.3}$ families of CG 14 x NERICA 10, WAB-56-104 x NERICA 4 had the highest number of tillers while NERICA 4 x NERICA 1 had the least number of tillers. The variation in the tillering ability of the $F_{2.3}$ families across sites could be due to the favourable growing conditions characterized by good soils with high water retention capacity at Kirogo Experimental Farm. Tillering ability in rice plant is a vital agronomic character for commercial grain production. Ibrahim et al., (1990) reported that effective tillers were the most reliable trait in selecting rice genotypes for higher grain yield. This observation was also supported by Zahid et al., (2005) who investigated 12 genotypes of coarse rice for yield performance in Kala, Pakistan and they reported significant variation in the number of effective tillers plant^{-1}. Therefore tillering in rice plays a vital role in determining grain yield since the number of tillers is closely associated to number of panicles plant^{-1}. Few effective tillers result into few panicles. However, excess tillering leads to high tiller mortality, small panicles, poor gain filling, reduced light penetration and reduced photosynthetic activity in some tillers leading to decline in grain yields (Efisue et al., 2014). This was evident in the $F_{2.3}$ families of CG 14 x NERICA 10. Higher number of productive tillers result in higher sink to source ratio, spikelet number, proportion of filled grains, leaf area per panicle and sink capacity (Choi and Kwon, 1985). Therefore, the $F_{2.3}$ families with high tillering ability like WAB-56-104 x NERICA 4 and NERICA 4 x MWUR 4 could exhibit the above mentioned characteristics.

4.8.1.5 Flag leaf length

Rice plants at Mwea Research Station exhibited the longest flag leaf compared to Kirogo Experimental Farm during the long and short growing seasons. The $F_{2.3}$ families of NERICA 13 x K 45, NERICA 10 x KUCHUM and WAB-56-104 x NERICA 4 had the longest flag leaves while MWUR 4 x NERICA 4 had the shortest flag leaf length. The variation in flag leaf length across sites could be due to the vegetative growth as a result of consistent supplemental irrigation at Mwea Research Station. The $F_{2.3}$ families of WAB-56-104 x NERICA 4 and NERICA 10 x KUCHUM exhibited longest flag leaves across the two environments. Rice plants with long flag leaf have large surface area to intercept sun light and they can undertake more photosynthetic activities thus generating more assimilates for grain filling leading to heavier grain weight and higher grain yield. The present study is in conformity with the earlier findings of Bharali and Chandra (1994) who reported a higher direct effect of flag leaf area on grain yield.

4.8.1.6 Panicle length

Compared to Kirogo Experimental Farm, the $F_{2.3}$ families at Mwea Research Station generally exhibited longer panicles. The $F_{2.3}$ families of NERICA 10 x KUCHUM had the longest panicle while NERICA 4 x NERICA 1 had the shortest panicle. The variation in panicle length across environments could be due to high vegetative growth observed at Mwea Research Station due to regular irrigation of the trial as a result of its closeness to the research station. The panicle length of rice plant determines the number of grains to be accommodated. The results further revealed that genotypes with long panicles contained more grains than short panicle genotypes. Similar results were reported by Efisue et al., (2014) who observed high grain yields in rice genotype IRBW-123 that exhibited longer panicle of 20.64 cm.

4.8.1.7 Number of panicles plant^{-1}

Number of panicles plant^{-1} was higher at Kirogo Experimental Farm than at Mwea Research Station across the two growing seasons.

The $F_{2.3}$ families of WAB-56-104 x NERICA 4 exhibited the highest number of effective tillers while MWUR 4 x NERICA 4 had the lowest number of effective tillers across environments. The variation in the number of panicles plant^{-1} across sites could be due to favourable growing conditions characterized by good soils with high water retention capacity at Kirogo Experimental Farm. Number of panicles plant^{-1} is the main determinant of rice grain yield (Zakayo, 2013). High grain yield is strongly associated with higher number of panicles plant^{-1}. The present results revealed that the number of panicles played a major role in determining grain yield and that any increase in the number of panicles plant^{-1} exhibited significant effect on grain yield. This investigation is in conformity with the findings of Zakayo (2013) who studied the variation and correlation among yield and yield components in lowland rice genotypes at Mwanza region of Tanzania. They reported that number of panicles plant^{-1} had a strong correlation with grain yield.

4.8.1.8 Number of filled grains panicle^{-1}

The $F_{2.3}$ families at Kirogo Experimental Farm exhibited the highest fertile grains panicle^{-1} compared to Mwea Research Station. The $F_{2.3}$ families of MWUR 4 x NERICA 4, WAB-56-104 x NERICA 4 had the highest number of fertile grains panicle^{-1} while NERICA 13 x K 45 had the lowest. The $F_{2.3}$ families displayed a wide range of variability for number of fertile grains panicle^{-1}. Babu et al., (2012) also reported significant variation ($P \leq 0.05$) for number of filled grains panicle^{-1} in rice genotypes. The genetic variability could be attributed soil fertility, plant nutrient translocation and the weather conditions during plant growth (Jamal et al., 2009).

The variation in soil moisture content could have contributed to differences observed in the number of fertile grains panicle^{-1}. Water deficit (Fig. 4.2) during the crop growing cycle resulted in major reduction in grain dry matter. Therefore cold damage and water stress experienced during the long rain season of 2017 could be the likely cause of shortage of assimilates supply to grain filling due to inhibition of important biochemical processes like photosynthesis (Yoshida, 1981). The higher the number of fertile grains panicle^{-1} the higher the grain yield. Luzi-Kihupi (1998) studied the interrelationship between yield and selected yield components in rice and revealed that plants with large panicles tend to have high grain filling.

4.8.1.9 Grain yield

The $F_{2.3}$ families had better yields at Kirogo Experimental Farm compared to Mwea Research Station. Highest grain yield was observed in the $F_{2.3}$ families of WAB-56-104 x NERICA 4, while NERICA 13 x K45 had the lowest grain yield. The parental line WAB-56-104 was the best grain yielder among the check varieties. The $F_{2.3}$ families of WAB-56-104 x NERICA 4 maintained high grain yields than the check Basmati 370 across sites. The variation in grain yield across sites could be due to favourable growing conditions characterized by good soils with high water retention capacity as well as rainfall distribution (Fig. 4.2) and diverse genetic composition of the $F_{2.3}$ families. Similar results were observed by Xing and Zhang (2010) who reported that rice varieties exhibit tremendous variation in grain yield due to diversity in genetic constitution. The $F_{2.3}$ families of WAB-56-104 x NERICA 4, NERICA 4 x NERICA 1, NERICA 4 x MWUR 4 and NERICA 10 x KUCHUM consistently maintained higher grain yields across sites suggesting a wider adaptability to varying environments. In order to improve grain yield of rice genotypes, breeders are required to focus on developing rice plants bearing more number of panicles with high tillering ability, this could lead to tremendous increase in gain yield. Grain yield of rice is determined by several agronomic characters such as days to heading, days to maturity, grain filling period, number of effective tillers, number of filled grains per panicle, panicle length and plant height (Halil and Necmi, 2005).

4.8.1.10 1000-grain mass

The $F_{2.3}$ families exhibited heaviest 1000-grain mass at both Mwea Research Station and Kirogo Experimental Farm during the long growing season. Rice plants had heavy 1000-grain mass at Kirogo Experimental Farm than at Mwea Research Satation. The $F_{2.3}$ families of WAB-56-104 x NERICA 4 had the heaviest 1000-grain mass, while NERICA 13 x K 45 had the lightest grains. The genetic variability exhibited by the $F_{2.3}$ families could be due to the presence of inherent genetic differences. Akinwale et al., (2011) estimated the genotypic and phenotypic coefficients of variation, broad sense heritability, genetic gain and correlations in rice cultivars grown at the IITA, Ibadan, Nigeria. They reported highly significant genotypic differences ($P \leq 0.001$) indicating that the genotypes constituted a pool of germplasm with adequate genetic variability. Osman et al., (2012) evaluated 13 upland rice genotypes for genetic variability of grain yield and yield characters at White Nile Research Station Farm, Wad Medani Sudan.

They reported a wide range of variability among the genotypes for most of the traits studied in both seasons. Grain weight is a secondary agronomic trait that determine rice grain yield (Jamal et al., 2009). The weight of the rice grain is determined by the capacity of the photosynthetic leaves to supply assimilates during the grain ripening period as well as by the capacity of the developing grains (sink) to accumulate imported assimilates (Ntanos and Koutroubas, 2002). Rice cultivars with high grain weight tend to have higher grain filling rate leading to higher assimilate accumulation and therefore, exhibit heavier grain weight (Jamal et al., 2009). In this study, the $F_{2.3}$ families of WAB-56-104 x NERICA 4 and MWUR 4 x NERICA 4 exhibited heavier grain weight indicating that these genotypes had higher grain filling rate among the tested genotypes. These results are in conformity with the earlier reports of Jeng et al., (2003) who reported high yield potential in newly bred super rice at Jiangsu China due to higher grain filling rate in the earlier flowering superior spikelets.

4.8.1.11 Correlation analysis of agronomic and yield traits in $F_{2.3}$ families

Direct selection for grain yield in rice plants is quite difficult because yield is a complex quantitative trait that is highly influenced by environment. As a result, high genotypic and environmental interactions may restrict the improvement of yield. Therefore, correlation studies between yield and yield characters are necessary in establishing a selection program because some of the yield components are less influenced by the growth environment and are easily heritable. The yield characters exhibit different associations among themselves and also with grain yield, and any unfavourable association between the desired characters may lead to limited genetic advance. Out of eleven agronomic characters studied, only number of tillers plant^{-1}, number of panicles plant^{-1} and number of filled grains panicle^{-1} were strongly correlated with grain yield suggesting the importance of these characters in determining grain yield. Therefore, selecting for number of tillers plant^{-1}, number of panicles plant^{-1} and number of fertile grains panicle^{-1} would lead to increase in grain yield. Golam et al., (2011) studied correlation analysis in 53 rice genotypes including 12 globally popular aromatic and 39 advanced breeding lines. They reported that the number of fertile tillers (r = 0.69), grain per panicle (r = 0.86) and fertile grain per panicle (r = 0.65) have a positive contribution to grain yield which supports the present finding. Although a negative trend was observed between duration to 50 % flowering (r = -0.24*), days to maturity (r = -0.24*), plant height (r = -0.29**), panicle length (r = -0.36**) and flag leaf length (r = -0.38**). However, these traits were not correlated with grain yield. The inverse relationship between grain yield and plant height indicate that higher grain yields would be realized by breeding for short statured rice plants. Tallness in rice plants reduce grain yield due to accumulation of assimilates in the culm and other vegetative parts rather that accumulating them in seed formation and grain filling (Yoshida, 1981). The negative association between 50 % days to flowering and days to maturity with grain yield implied that early flowering and maturing rice genotypes do not allow the production of sufficient assimilates for the production of many effective panicles and fully filled grains hence leading to reduction in grain yields. Similar results were reported by Golam et al., (2011) who also observed a negative correlation between days to heading, days to maturity and plant height with the most important character yield. Plant height exhibited a highly significant and positive correlation with flag leaf length (r = 0.556**) and panicle length (r = 0.622**) indicating that tallness in rice plant leads to accumulation of assimilates in the vegetative parts hence leading to active growth and increase in length of flag leaf as well as the panicle (Yoshida, 1981).

Plant height showed a negative and non-significant association with 1000 grain mass suggesting that tallness in rice plant leads to accumulation of assimilates in the vegetative parts thus reducing the capacity of the sink (developing grains) to import assimilates hence reducing grain filing that leads to lighter grains. These findings are supported by Qamar et al., (2005) who revealed that plant height exhibited negative and non-significant correlations both at genotypic and phenotypic levels with productive tillers, grain yield per plant and 1000 grain weight. Therefore, the number of tillers plant^{-1}, number of panicles plant^{-1} and fertile grains panicle^{-1} were strongly correlated with grain yield and also among themselves indicating that simultaneous selection of these characters would result in yield improvement.

4.8.2 Physical grain quality

Length to width (L/W) ratio is important in classification of grain shape. A higher value of over 3 indicate a slender shape, a value between 2.1 and 3.0 reveals a medium shape and a lower value indicate a bold or round shape (Rita and Sarawgi, 2008). In this study, the $F_{2.3}$ families of NERICA 4 x MWUR 4, NERICA 10 x KUCHUM and NERICA 4 x NERICA 1 exhibited higher L/W ratio indicating that these genotypes were slender in shape. The $F_{2.3}$ families of NERICA 13 x K45, WAB-56-104 x NERICA 4, CG 14 x NERICA 10 and MWUR 4 x NERICA

4 exhibited an L/W ratio of between 2.1 and 3.0 suggesting that they were medium in grain shape. The check variety Basmati 370 exhibited a slender shape with a relatively higher L/W ratio than the non-Basmati rice genotypes. Similar findings were observed by Yadav et al., (2016) who studied the physico-chemical, cooking, pasting and textural properties of some Indian rice varieties of Basmati and non-Basmati. They reported a length to width ratio of more than 3.0 for all the grains of all the rice cultivars studied but the L/W ratio of Basmati grains was significantly higher than non-Basmati grains. Compared to all the $F_{2.3}$ families, the check variety Basmati 370 exhibited the highest grain length. Similar findings were observed by Yadav et al., (2007) who reported a significantly higher grain length in Indian Basmati rice than non-Basmati varieties. Rice grain quality depends on physico-chemical properties which are greatly influenced by the genotype of the plant (Kishine et al., 2008). Assessing the physical dimensions of rice cultivars is very important because the physical appearance of milled rice is important to the consumer, miller and the marketer (Fofana et al., 2011). Rice breeders consider grain shape and grain size as the most important rice quality parameters when developing new rice varieties for commercial production because consumer preference for grain shape and size vary from one group of consumers to another (Rani et al., 2006). Long and slender rice grains are mostly preferred by many consumers and such grains normally fetch higher prices at the international market (Singh et al., 2010). Therefore, the physical attributes exhibited by NERICA 4 x MWUR 4, NERICA 10 x KUCHUM and NERICA 4 x NERICA 1 can be exploited in a breeding program designed to improve the grain quality of local rice cultivars.

4.8.2 Chemical grain quality

The cooking and eating characteristics of rice are usually determined by the properties of starch that constitutes 90 % of the milled grain. Alkali spreading value, gelatinization temperature, gel consistency and aroma directly influence the cooking and eating qualities of milled rice (Bahmaniar and Ranjbar, 2007). Gelatinization temperature is the temperature at which all the starch in the rice grain begins the process of cooking and at this stage the starch granules absorb water and irreversibly lose their crystalline nature. Starch in rice grain usually gelatinizes between 55 to 79^{o}C (Singh et al., 2000). The gelatinization temperature of rice varieties can be classified as low (55 to 69^{o}C), intermediate (70 to 74^{o}C) and high (75 to 79^{o}C) (IRRI, 2000). The extent of the spreading of the milled rice kernels in a dilute alkali solution (1.7 % KOH) is

strongly associated with gelatinization temperature (Singh and Khush, 2000). The study showed that the $F_{2.3}$ rice families of NERICA 4 x NERICA 1 and MWUR 4 x NERICA 4 showed alkali digestion scale 6 implying that the grain of these rice genotypes dispersed and merged with collar in dilute alkali solution while WAB-56-104 x NERICA 4 showed alkali digestion scale 7 suggesting that the grain completely dispersed and intermingled in dilute alkali solution. The $F_{2.3}$ families of NERICA 10 x KUCHUM showed scale 4 indicating that the grain was swollen, collar complete and wide while NERICA 4 x MWUR 4 showed scale 2- grain swollen while NERICA 13 x K45 and CG 14 x NERICA 10 showed scale 3- grain swollen, collar incomplete and narrow. The high gelatinization temperature exhibited by CG 14 x NERICA 10, NERICA 4 x MWUR 4, NERICA 13 x K45 and NERICA 10 x KUCHUM suggested that the starch granules in these genotypes required higher temperatures to start the process of cooking in contrast WAB-56-104 x NERICA 4, NERICA 4 x NERICA 1 and MWUR 4 x NERICA 4 took shorter time to initiate the process of cooking. The variation in gelatinization temperature among the rice genotypes could be attributed to higher ambient temperature during grain ripening period that led to formation of starch with high gelatinization temperature. Dela Cruz *et al.,* (1989) reported that gelatinization temperature is influenced by environmental conditions such as temperature during grain development. The $F_{2.3}$ families with low gelatinization temperature disintegrated completely in dilute alkali solution and took shorter time to cook while the check Basmati 370 with intermediate gelatinization temperature showed partial disintegration in the alkali solution.
The $F_{2.3}$ families that exhibited high gelatinization temperature remained largely unaffected in dilute alkali solution and they took longer time to cook. These results are in conformity with the findings of Shayo *et al.,* (2006) who observed high gelatinization temperature in all the rice genotypes studied at Morogoro, Tanzania and they reported that the rice cultivars Supa, Salama and Kihogo red took longer time to cook and hence required more water during cooking.

Gel consistency measures the tendency of the cooked rice to harden upon cooling and it is a good index of cooked rice texture (Tang *et al.,* 1991). Based on gel consistency, rice varieties can be classified into soft gel (61 to 100 mm), medium (41 to 60 mm) and hard gel (26 to 40 mm) (Dela Cruz and Khush, 2000). The variation in the gel consistency indicated that $F_{2.3}$ families with soft gel cooked more tenderly and remained soft even upon cooking while those with hard gel harden faster upon cooling than those with medium and soft gel. These results are in agreement with the findings of Oko *et al.,* (2012) who reported that the rice cultivars E4-197 and Faro 14 were preferred by consumers due to their soft texture upon cooking. Therefore, rice varieties with soft gel are mostly preferred by consumers because the cooked rice is so tender while eating.

Aroma is an important quality trait that influences the eating qualities and consumer acceptability of a particular rice variety. Aromatic rice varieties command premium prices at the international market (IRRI, 2000). In this study, none of the genotypes tested exhibited strong aroma like the check Basmati 370. Shayo *et al.,* (2006) observed that longer cooking of the rice grains will have a considerable effect on the test and aroma of the cooked rice because some volatile compounds are likely to be lost during cooking. The test panel preferred the check variety Basmati 370 as far as aroma was concerned. These results are in agreement with the findings of Luzi-Kihupi *et al.,* (2007) who evaluated the cooking and eating qualities of mutant lines obtained from irradiating a local rice cultivar and they reported that the test panel rated Supa parent variety as good in terms of aroma and SSD 7 as normal. Therefore, the results of the sensory test revealed the need for further improvement of this trait (aroma) in the $F_{2.3}$ families evaluated.

4.8.3 Correlations between physico-chemical characters

Cooking time was strongly correlated with gelatinization temperature and gel consistency implying that rice genotypes with high gelatinization temperature required more cooking time but those with low gelatinization temperature took short time to cook and had soft texture. Similar findings were also reported (Oko *et al.,* 2012 and Yadav *et al.,* 2016). Cooking time was negatively correlated with grain length suggesting that an increase in grain length result in reduction in cooking time. Alkali spreading value was negatively correlated with gelatinization temperature suggesting that gelatinization temperature decreases with increase in alkali digestion value. Similar results were also reported (Singh *et al.,* 2012 and Basri *et al.,* 2015). Low value of alkali digestion indicates that the rice kernels are largely unaffected in dilute alkali solution and therefore require high temperature to cook. This is contrary to the findings of Tamu (2015) who reported a strong and significant correlation of alkali spreading value with gelatinization temperature. Grain length was strongly correlated with grain width suggesting that an increase in grain length results in a significant increase in grain width.

This is contrary to the findings of Seraj *et al.,* (2013) who reported significant and negative correlation of grain length with grain width. Gel consistency was negatively correlated with grain length and grain width implying that rice genotypes with long grain and high grain width have low gel consistency. Correlation analysis is an important tool that helps plant breeders to indirectly select for a farmer preferred trait (Seraj *et al.*, 2013). Therefore, correlation studies for most of the physico-chemical traits suggested that efforts aimed at selecting rice varieties with improved cooking quality traits requires a consideration of the physico-chemical qualities of the rice grain (Oko *et al.*, 2012).

4.8.4 Conclusion

Out of the 16 segregating populations evaluated, three rice families namely WAB-56-104 x NERICA 4, MWUR 4 x NERICA 4 and NERICA 4 x NERICA 1 were early maturing, exhibited short to intermediate plant height and consistently maintained higher grain yields across sites suggesting a wider adaptability to varying environments. In addition these three rice families exhibited better culinary and physico-chemical qualities. However, the check variety Basmati 370 was outstanding for physical grain quality and aroma compared to the non-Basmati rice genotypes. Therefore, the sensory panel preferred the check variety Basmati 370 as far as aroma was concerned suggesting that Basmati 370 has implication for future breeding. These grain quality characters influence the choice of farmers and consumers in adopting a rice variety, marketability and in determining the price of the marketed grains. Therefore, plant breeders need to consider these culinary qualities in developing new rice varieties in order to increase adoption, acceptability and consumption of the rice variety.

CHAPTER FIVE

5.0 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 Discussion

The objective of this study was to i) to determine combining ability and heterosis for agronomic and yield traits in indica and japonica rice crosses and ii) to select for yield potential, earliness and grain quality in $F_{2.3}$ rice families.

Combining ability analysis revealed significant GCA and SCA variance for most of the agronomic and yield characters studied suggesting the importance of both additive and non-additive gene actions in the expression of these yield traits. Previous studies reported the influence of both additive and non-additive gene action in the inheritance of agronomic and yield traits (Chakraborty et al., 2009; Mirarab et al., 2011; Padmavathi et al., 2012 and Malemba et al., 2017). The rice parents Basmati 370, Basmati 217, K_2-54 and Komboka were good general combiners for grain yield. The higher magnitude of GCA variance (fixable genetic component) suggested a major role of additive gene action in the expression of characters such as duration to 50 % flowering, number of spikelet's panicle^{-1}, number of fertile grains panicle^{-1}, and number of productive tillers plant^{-1}, grain yield and 1000-grain mass. Previous research also reported the predominance of additive gene action in the inheritance of days to maturity, number of productive tillers plant^{-1}, number of panicles per plant and 1000 grain weight (Dar et al., 2014). Therefore, it is suggested that a breeding method that would take care of the fixable gene effects and as well as maintain heterozygosity for exploiting the dominance effects may be more efficient for the improvement of grain yield. Hence, a simple selection procedure followed by pedigree breeding is sufficient to improve the traits influenced by additive gene action (Chakraborty et al., 2009). The F_1 hybrids K_2-9 x Komboka, K_2-9 x Basmati 370, K_2-54 x *Dourado precoce* and K_2-54 x Basmati 217 were good specific combiners for grain yield. All these high yielding hybrids originated from high x high GCA combinations attributable to additive x additive type of gene actions thus the yield potential of these hybrids can be fixed in subsequent generations (Sandhyakishore *et al.,* 2011). The heterosis study revealed that hybrid vigour for grain yield was due to interaction of many yield components such as days to maturity, panicle length, number of tillers plant^{-1}, number of panicles plant^{-1} and filled grains panicle^{-1} (Veeresha *et al.,* 2015).

In this study, the hybrids K_2-9 x Basmati 370, K_2-8 x Basmati 217, K_2-54 x Basmati 217 and K_2-9 x Komboka exceeded the yield level of the check variety (Basmati 370) by 20 % suggesting that they were high yielding and have the potential for commercial utilization. In addition, the hybrids K_2-9 x NERICA 1, K_2-8 x NERICA 1, K_2-54 x Basmati 370, K_2-54 x PAN 84, K_2-54 x IR-27-93-80-1 and K_2-54 x *Dourado precoce* were early maturing over the better parent (NERICA 1) suggesting the possibility of exploiting these hybrids in developing early maturing lines. Similar findings were also reported (Rahimi *et al.*, 2010).

The evaluation of $F_{2.3}$ families for yield potential, earliness and grain quality revealed a high genetic variation among the $F_{2.3}$ families. The $F_{2.3}$ families used in the study were from diverse genetic sources, some of the genotypes were locally improved at Industrial Crops Research Center in Mwea while others were introductions generated from interspecific hybridization between cultivated rice species of *Oryza sativa* and *Oryza glabberima*. This explains the genetic variability among the tested $F_{2.3}$ families. Ovung et al., (2012) reported that the presence of large genetic variability among rice genotypes could be due to diverse sources of germplasm as well as the influence of the growth environment. Similar genetic variations among diverse genotypes were also reported by (Akinwale et al., (2011) and Rashid et al., (2013) who observed significant genotypic variations among rice genotypes for all the agronomic and yield traits studied.

Evaluation of the $F_{2.3}$ families revealed that WAB-56-104 x NERICA 4 and NERICA 10 x KUCHUM and NERICA 4 x NERICA 1 had short duration to maturity. Therefore, these short genotypes can be used as parents by breeders to develop early maturing genotypes. The results further revealed that the $F_{2.3}$ families of WAB-56-104 x NERICA 4 and NERICA 10 x KUCHUM and NERICA 4 x NERICA 1 with relatively short to intermediate height exhibited higher grain yields across sites. The higher number of productive tillers exhibited by these genotypes was due to higher sink to source ratio, spikelet number, proportion of filled grains, and leaf area per panicle and sink capacity (Choi and Kwon, 1985). The high yielding $F_{2.3}$ families could be selected for grain yield improvement in a breeding program because they consistently maintained higher grain yields in all locations suggesting a wider adaptability to varying environments. In order to improve grain yield of rice genotypes, breeders are required to focus on developing rice plants bearing more number of panicles with high tillering ability, this could lead to tremendous increase in gain yield. Grain yield is determined by several agronomic traits such as days to heading, days to maturity, grain filling period, number of effective tillers, number of filled grains per panicle, panicle length and plant height (Halil and Necmi, 2005).

Evaluation of the physical dimensions of rice cultivars is very important because the physical appearance of milled rice is important to the consumer, miller and the marketer (Fofana et al., 2011). In this study, the $F_{2.3}$ families of NERICA 4 x MWUR 4, NERICA 10 x KUCHUM and NERICA 4 x NERICA 1 exhibited higher L/W ratio suggesting slender grain shape. The $F_{2.3}$ families of NERICA 13 x K45, WAB-56-104 x NERICA 4, CG 14 x NERICA 10 and MWUR 4 x NERICA 4 exhibited an L/W ratio of between 2.1 and 3.0 suggesting a medium grain shape. Slender grain shape was also reported in upland rice varieties (Shejul *et al.,* 2013 and Chukwuemeka *et al.*, 2015). Previous studies reported medium grain shape category in local rice varieties (Singh *et al.,* 2012 and Basri *et al.*, 2015) The high gelatinization temperature exhibited by CG 14 x NERICA 10, NERICA 4 x MWUR 4, NERICA 13 x K45 and NERICA 10 x KUCHUM suggested that the starch granules in these genotypes took longer time to start the process of cooking compared to WAB-56-104 x NERICA 4, NERICA 4 x NERICA 1 and MWUR 4 x NERICA 4 that took shorter time to initiate the process of cooking. The variation in gelatinization temperature among the rice genotypes could be attributed to higher ambient temperature during grain ripening period that led to formation of starch with high gelatinization temperature (Singh *et al.*, 2010). The variation in the gel consistency indicated that $F_{2.3}$ families with soft gel cooked more tenderly and remained soft even upon cooking while those with hard gel harden faster upon cooling than those with medium and soft gel. In this study, none of the genotypes tested exhibited strong aroma like the check variety Basmati 370.

5.2 Conclusions

The analysis of combining ability and heterosis for agronomic and yield traits between indica and japonica rice crosses showed that the parental lines Basmati 370, Basmati 217, K_{2}-54 and Komboka were good general combiners for grain yield. In contrast, their crosses K_{2}-9 x Komboka, K_{2}-9 x Basmati 370, K_{2}-54 x *Dourado precoce* and K_{2}-54 x Basmati 217 were good specific combiners and expressed better heterotic effects for grain yield. The agronomic and yield traits such as days to 50 % flowering, days to maturity, number of tillers plant^{-1}, number of spikelet's panicle^{-1}, number of effective tillers plant^{-1}, number of fertile grains panicle^{-1} and grain yield were governed by additive gene action while non-additive gene action was dominant in plant height, panicle length, flag leaf length and 1000 grain weight. Therefore, these findings do not support the null hypothesis.

Evaluation of the $F_{2.3}$ families for yield potential, earliness and grain quality showed that the three families namely WAB-56-104 x NERICA 4, MWUR 4 x NERICA 4 and NERICA 4 x NERICA 1 out of 16 populations studied were early maturing, exhibited short to intermediate plant height and consistently maintained higher grain yields across sites suggesting a wider adaptability to varying environments. In addition these three rice families exhibited better culinary and physico-chemical qualities. However, the check variety Basmati 370 was outstanding for physical grain quality and aroma compared to the non-Basmati rice genotypes suggesting that Basmati 370 has implication for future breeding. Therefore tremendous yield potential, earliness and high grain quality exist among the $F_{2.3}$ families studied.

5.3 Recommendations

1. The high yielding parental genotypes are recommended as donors in rice breeding program while their crosses K_{2}-9 x Komboka, K_{2}-9 x Basmati 370, K_{2}-54 x *Dourado precoce* and K_{2}-54 x Basmati 217 could be advanced to F_6 or F_7 to ascertain their yield potential and further evaluated in a wide range of environments.
2. The $F_{2.3}$ families of WAB-56-104 x NERICA 4, CG 14 x NERICA 10, MWUR 4 x NERICA 4 and NERICA 13 x K45 are recommended for further improvement of physical grain quality.
3. The check variety Basmati 370 should be used a donor for the improvement of aroma, physical grain quality of local rice cultivars.
4. Evaluation of the $F_{2.3}$ families for all the grain quality characters is recommended in order to guide the plant breeder in selecting rice genotypes with farmer preferred traits in order to increase adoption of the variety when released for commercial production.
5. The early maturing and high yielding $F_{2.3}$ families of NERICA 4 x NERICA 1, WAB-56-104 x NERICA 4, NERICA 4 x MWUR 4 and NERICA 10 x KUCHUM were still segregating and should be advanced to F_6 or F_7 for further selection inorder to ascertain their yield potential.

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APPENDICES

Appendix 1 Weather data for season one

Season one (Aug-Dec 2016)						
	Mwea weather Data			**Kirogo weather Data**		
Month	**Relative Humidity (%)**	**Temperature (ºC)**	**Rainfall (mm)**	**Relative Humidity (%)**	**Temperature (ºC)**	**Rainfall (mm)**
August	60.89	20.59	0.06	70.89	19.59	1.56
September	58.59	21.61	0.03	75.59	20.61	0.13
October	52.77	23.7	0.02	72.77	21.7	0.08
November	73.79	21.78	0.81	73.79	18.78	1.07
December	71.07	21.21	0.29	71.07	20.21	2.38
Mean	**63.42**	**21.78**	**0.24**	**72.82**	**20.18**	**1.04**
Total	**317.11**	**108.89**	**1.21**	**364.11**	**100.89**	**5.22**

Appendix 2 Weather data for season two

Season two (Apr-Sept 2017)						
	Mwea weather Data			**Kirogo weather Data**		
Month	**Relative Humidity (%)**	**Temperature(C)**	**Rainfall (mm)**	**Relative Humidity (%)**	**Temperature(C)**	**Rainfall (mm)**
April	77.84	22.92	1.26	79.33	22.75	5.65
May	79.91	21.26	2.68	79.27	21.03	3.37
June	77.56	20.21	0.33	76.31	19.91	0.393
July	68.59	22.24	0.55	72.15	22.29	0.57
August	66.91	23.91	1.28	70.46	23.98	1.51
September	60.89	21.78	0.48	73.79	20.59	1.63
Mean	**71.95**	**22.053**	**1.097**	**75.22**	**21.76**	**2.19**
Total	**431.7**	**132.32**	**6.58**	**451.31**	**130.55**	**13.123**