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AGRO-MORPHOLOGICAL, NUTRITIONAL AND PHYTOCHEMICAL CHARACTERIZATION OF BAMBARA GROUNDNUT LANDRACES UNDER VARYING AGRO-ECOLOGICAL CONDITIONS IN EMBU COUNTY, KENYA

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DECLARATION

This thesis is my original work and has not been presented elsewhere for a degree award or any other award.

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In loving memory of my dear brother Vincent Kirui and in honour of beloved parents, Eunice and Samuel Steve Cheruiyot and my dear siblings whose love and support have been my greatest blessings.

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LIST OF ABBREVIATIONS AND ACRONYMS

AEZ	Agro-ecological zones
ANOVA	Analysis of Variance
AOAC	Association of Official Agricultural Chemists
ASL	Above sea level
BAMNET	International Bambara groundnut Network
FAO	Food and Agriculture Organization
FSSAI	Food Safety and Standards Authority of India
GEI	Genotype-environment interactions
HSD	Tukey's Honest Significant Difference
IITA	International Institute of Tropical Agriculture
IPGRI	International Plant Genetic Resource Institute
LM4	Lower Midland 4
PCA	Principal Component Analysis
RCBD	Randomized Complete Block Design
SAS	Statistical Analysis System
SDG	Sustainable Development Goals
SNK	Student Newman Keul
UM2	Upper Midland 2
UN	United Nations
UPGMA	Unweighted Pair Group Method with Arithmetic Average
XLSTAT	Excel Statistics software

LIST OF SYMBOLS

℃	Degree Celsius
Ca	Calcium
cm	Centimetres
Cu	Copper
E	East
Fe	Iron
h	Hour
HCl	Hydrochloric acid
K	Potassium
l	Litres
m	Meters
Mg	Magnesium
mg	Milligrams
ml	Millilitres
N	North
Na	Sodium
Na_2CO_3	Sodium carbonate
nm	Nanometer
ppm	Parts per million
S	South
t ha^{-1}	Tonnes per hectare
Zn	Zinc

ABSTRACT

Bambara groundnut is an underused leguminous crop in the Fabaceae family that originated from West Africa. Agro-morphological and nutritional diversity studies to determine Bambara groundnut landraces with superior end user preferred traits are limited. The objective of this study was to determine the agro-morphology, nutritional and phytochemical profiles of Bambara groundnut landraces grown in Kenya. For two cropping seasons, field experiments were conducted in Embu West (Kangaru), Mbeere North (Ishiara) and Mbeere South (Kiamuringa) sub-counties, in Embu County. Three replicates of the field tests were set up using a Randomized Complete Block Design (RCBD). All the agro-morphological data were collected based on International Plant Genetic Resource Institute (IPGRI) descriptors for Bambara groundnuts. Five Bambara groundnut plants were selected randomly from each plot and tagged for purpose of data collection. Both qualitative and quantitative data was organized in a matrix and subjected to cluster and Principal Component Analysis (PCA) in order to select the landraces with superior agro-morphological traits. Using XLSTAT software 2023, analysis of variance (ANOVA) was also performed on quantitative data. Using Tukey's Honest Significant Difference (HSD) at a 95% level of confidence, the means were separated. Pearson correlation was conducted to assess the strength of linear relationship between the agro-morphological traits. On the other hand, phytochemical, nutritional and composition were analysed using the standard procedures. Nutritional and phytochemical data were subjected to ANOVA, cluster analysis and Principal Component Analysis (PCA). Pearson correlation analysis was also done to determine how the nutritional and phytochemical variables related to one another. Higher yields were obtained in the first season compared to the second seasons in all the locations. There were significant location effects for all the quantitative traits. A combined analysis of variance revealed that there were significant differences ($P<0.05$) in all the agro-morphological variables evaluated except for days to first flowering, days to 50% flowering and plant height. The yields ranged from 0.84-5.01 t ha^{-1} (Kiamuringa), 0.69-3.14 t ha^{-1} (Ishiara) and 0.60-2.44 t ha^{-1} (Kangaru). The yield correlated positively and significantly ($P<0.05$) with days to first flowering, weight of 100 seeds, days to 50% flowering and number of seeds per plant. The landraces BS-107, LU-122, LU-121, BS-134 and BS-144 are among the high yielding landraces identified and can be adopted for cultivation. In the pooled data for both seasons, there were significant variations ($P<0.05$) in every phytochemical and nutritive trait. The total ash ranged from 3.17 to 4.69%; moisture content from 3.47 to 6.24%; fats from 4.56 to 7.02% and crude protein from 21.18 to 26.00%. Zinc ranged from 0.06 to 0.42 mg/100g; Iron levels from 4.07 to 5.13 mg/100g; Potassium from 819.34 to 1,133.80 mg/100g and Sodium from 25.14 to 129.66 mg/100g. The saponins levels ranged from 0.82 to 1.06 mg/100g; tannin from 0.01 to 0.04 mg/g; flavonoids from 4.07 to 8.45 mg/100g and alkaloids from 0.01 to 0.12 mg/100g. The landraces with high nutritional value such as BG-125, BS-148 and BS-145, among others, are recommended to farmers for adoption. The landraces with high levels of phytochemicals are recommended to pharmaceutical and nutraceutical industries for exploitation of their medicinal value. These may include BS-104 for flavonoids and MU-137 for saponins. The nutritional value of landraces BS-114, LU-123 and KS-108 should be enhanced by lowering their sodium content levels.

CHAPTER ONE
INTRODUCTION

1.1 Background of the study

Bambara groundnut (*Vigna subterranea)* is an underutilized legume in the Fabacea family, widely cultivated in African and Asian nations (Khan *et al*., 2020). Bambara groundnut (2n = 2x = 22) is thought to have come from West Africa specifically an area called as 'Bambara' in Central Mali (Temegne *et al*., 2018). Bambara groundnut is named after its similarity in pod formation to that of groundnut (Amadou *et al*., 2001). It's general knowledge that Bambara beans are a "poor man's" crop in addition to being "women's crop" cultivated solely for sufficient supply of food (Ntundu *et al*., 2006). Nevertheless, it was just referred to as one of the new millennium's crops (Ahmad, 2012). This is because ability to thrive in nutrient-poor soils, drought tolerance traits and nutritional value puts Bambara groundnut in the category of crops that are climate resilient hence promotion of this crop particularly in drought prone areas should be done. Bambara groundnut can tolerate pests and diseases and naturally enrich the soil with nutrients by fixing nitrogen from the atmosphere hence lowering the requirement for organic and synthetic fertilizers (Tibe *et al.*, 2007). This is crucial in areas with poor soil and helps poor-resource farmers save money on fertilizers.

In Kenya, the legume has different local names that include tsimbande (Luhya), njugu mawe (Swahili) and nzugu mawe (Giriama) (Chelangat *et al*., 2023). The legume is mainly grown in Western regions and to some extent, Coastal and Nyanza regions but is unpopular in other Kenyans regions. Africa's sub-Saharan region is the top Bambara groundnut growers where Cameroon, Burkina Faso and Niger contributed 74% of the total output in the world for the year 2018 (Majola *et al*., 2021). According to Majola *et al*. (2021) from 1999 through 2018, the Africa's Sub-Saharan region produced between 0.65 and 0.78 tons per hectare of Bambara groundnut . This is very low since the crop is known to have production potential of over 3 t ha^{-1} (Coyne & McGee, 2013). Major factors that hinder the production of Bambara groundnut include poor agricultural practices, poor-quality seeds and use of low-yielding varieties (Majola *et al*., 2021).

Due to shifts in dietary patterns and the recognition of the significance of readily available local crops, the utilization of underused crops as human food has grown (Xu

et al., 2021). Bambara groundnut is primarily cultivated for local use and is sometimes regarded as a complete meal due to its macronutrient composition, which is well-balanced (Khan *et al*., 2020). It contains 5.5% fiber, 23.6% protein, 64.4% carbohydrate and 6.5% fat. The crop also contains considerable amount of many minerals including Fe (3.6 mg), Na (75.25 mg), K (1723.25 mg) and Ca (360 mg) in 100 g of sample (Chandra *et al*., 2017). A significant share of the population of developing nations consume carbohydrate based diets because of scarcity and unaffordable minerals, protein based food and vitamins (Murevanhema & Jideani, 2013). When compared to sources of protein derived from animals, pulses and legumes like Bambara groundnut are less expensive (Tan *et al*., 2020). Because Bambara groundnut has high lysine content but low methionine levels, it pairs well with grains like maize, which lacks enough lysine but is rich in methionine (Boye *et al*., 2010). Considering its high level of protein content, Bambara groundnut together with other local protein-rich sources can reduce the dietary problems in underdeveloped nations in the tropics (Massawe *et al*., 2005).

Bambara groundnut has several uses that could potentially benefit health. In South Africa, raw seeds of Bambara groundnut is chewed and swallowed by pregnant women to treat morning sickness as it's known to be remedy to vomiting and nausea (Koné *et al*., 2011). The grains are often chewed as a remedy for a swelling jaw while flour is used as a treatment for rashes in the skin (Akpalu *et al*., 2013). It's thought that green leaves can stop vomiting (Minka & Bruneteau, 2000). In Senegal, ocular epilepsy and infected wounds are treated with sap extracted from Bambara groundnut leaves while a mixture of Bambara seeds powder and with water is used as a treatment for cataract (Murevanhema & Jideani, 2013). Water from steamed seeds of Bambara groundnut is used to remedy diarrhea by Kenyan Luo tribe (Atoyebi *et al*., 2017). However, its nutritional potential is limited by the existence of phytochemicals such as saponins, flavonoids and alkaloids that make nutrients less available in food (Unigwe *et al*., 2018). Some phytochemicals such as tannins have been found to have anticancer and antioxidant properties that may promote health (Daffodil *et al*., 2015).

In spite of the fact that Bambara groundnut is a traditional prominent food in Western and to some small extent, Nyanza and Coastal parts of Kenya, it's less known in other parts of the country (Oyeyinka *et al*., 2017). The crop holds great promise for enhancing

nutritional and food security in dry areas where malnutrition remains a major public health problem (Mubaiwa *et al*., 2018). However, it needs more promotion as both a food and a crop to ensure its adoption in such areas where it is little known. Promotion of this crop in new areas should be preceded by selection of the most suitable accessions in the target areas through agro-morphological and nutritional assessment of the available accessions.

1.2 Statement of the problem

In spite of tremendous economic and agronomic potential of Bambara groundnuts, their production has traditionally been restricted to Western, Nyanza, and the coastal regions. The drought tolerance traits, ability to grow and yield in poor soils and nutritional value puts Bambara groundnut among the list of climate-smart crops that needs to be promoted in drought prone areas. Nevertheless, the crop has been underutilized in such areas due to the scarcity of information on its agro-morphological and nutritional characteristics. Consequently, the farmers in such areas continue to grow common crops such as maize and beans, which are usually climate-sensitive and often fail to yield under prolonged drought and impoverished soils. Considering the challenges caused by climate change, it's crucial to evaluate the potential of climate-smart crops like Bambara groundnuts in marginal areas which forms the largest part of Kenya. However, farmers' preference is mainly guided by their knowledge on agronomic performance and nutritional value of a crop. These traits are usually genetically conferred but modified by other factors including climate and soils. This underscores the need to assess the agro-morphological and nutritional performance of different Bambara groundnut landraces in diverse agro-ecological conditions in Embu County.

1.3 Justification

Bambara groundnut is a high value horticultural crop whose highly nutritious leaves and seeds fetches a premium price in the market. The crop is also drought tolerant thus has enormous possibility to improve nutritional and food security in areas prone to drought where malnutrition remains a major public health problem. Because of its rich nutrient content, Bambara groundnut is considered a complete diet and can serve as a tool to improve human nutrition and food security as a repository of vital nutrients (Olaleye *et al*., 2013). This makes it pertinent to the diet planning of low-income individuals who cannot afford pricey animal-based protein (Ndidi *et al.*, 2014)

particularly those who reside in marginal locations with deficient soils and a high risk of drought. Successful adoption of Bambara groundnut in such areas would cushion the rural communities from food and nutritional insecurity. Information on agro-morphological variation and nutritional profile among various Bambara groundnut landraces under varying agro-ecological conditions in Kenya will generate the baseline information for promotion of this crop in areas where it's less known. In addition, this information will be useful to plant breeders in developing Bambara groundnut varieties with user-preferred traits.

1.4 Hypotheses

1. There is no significant variation in agro-morphological traits among different Bambara groundnuts landraces under varying agro-ecological conditions in Embu County, Kenya.
2. There is no significant difference in nutritional and phytochemical composition among selected Bambara groundnut landraces in Kenya.

1.5 Objectives of the study

1.5.1 Broad objective

To evaluate the agro-morphological, nutritional and phytochemical characteristics of different Bambara groundnut landraces under varying agronomic conditions in Embu County, Kenya.

1.5.2 Specific objectives

1. To evaluate agro-morphological variation among different Bambara groundnut landraces using agronomic and morphological traits under varying agro-ecological conditions in Embu County, Kenya.
2. To determine the nutritional and phytochemical composition of different Bambara groundnut landraces in Kenya.

CHAPTER TWO
LITERATURE REVIEW

2.1 Botanical description of Bambara groundnuts

Bambara groundnut is an annual leguminous crop belonging to the Leguminosae family and the Papilionodease subfamily (Basu *et al*., 2007). The crop has well-established tap roots and with stems having multiple side branches from which leaves emerge (Majola *et al*., 2021). As stated by Basu *et al*. (2007), trifoliate leaves, a tall, stiff, grooved petiole, and a green or purple base characterize this plant. As reported by Basu *et al*. (2007), the way in which pods are produced resembles groundnuts. Following fertilization, the stem of the pale yellow flowers slants downward, forcing the growing pods towards the ground, in which it develops and flourish (Amadou *et al*., 2015). The mature pods range in colour from yellow to a reddish dark brown, are indehiscent, and are frequently wrinkled (Basu *et al*., 2007). The dried pods are over half an inch long, spherical, and wrinkled with each pod containing one or two round or oval firm seeds with multicolored and smooth testa (Khan *et al*., 2021). Majola *et al*. (2021) stated that the Bambara bean seeds comes in a variety of colors, including brown, black, red, cream, yellow and purple.

2.2 Uses of Bambara groundnut

The principal use of Bambara groundnuts is as food for humans (Adeleke *et al*., 2018). The crop is frequently eaten in form of a snack after being roasted or boiled (Mubaiwa *et al*., 2017). Owing to their roughness, dried seeds are hard to grind into a powdery form, but once they are, excellent flat cakes and bread can be prepared (Harouna *et al*., 2018). The groundnuts can be roasted and consumed as candy (Mohammed *et al*., 2016), crushed and added to soup (Murevanhema & Jideani, 2013) or can be roasted and ground to make coffee-like beverage (Hillocks *et al*., 2012). The flour from Bambara groundnut seeds can be used to create a calorie-dense, thick and sticky porridge (Mayes *et al*., 2012). Apart from its application in the treatment of skin rashes, Bambara groundnut flour is also frequently eaten to reduce jaw swelling (Akpalu *et al*., 2013). To stop vomiting, green leaves are consumed (Minka & Bruneteau, 2000). Kenyan Luos utilize water from cooked Bambara groundnut seeds as a treatment for diarrhea (Atoyebi *et al*., 2018).

2.3 Agronomic performance of Bambara groundnut

Bambara groundnuts are similar to peanut (*Arachis hypogaea*) in both cultivation and habit. In agro-ecological areas with low annual rainfall, Bambara groundnut is frequently cultivated in rotation with sorghum (*Sorghum bicolor*), cowpea (*Vigna unguiculata*) and peanut (*Arachis hypogea*) as well as maize (*Zea mays*), sorghum (*Sorghum bicolor*) and millet (*Pennisetum glaucum*) (Hillocks *et al*., 2012). Bambara groundnut can be introduced to cycles of crop rotation to help in preserving fertility of the soil and interrupt pest and disease cycles, which benefits farmers whose access to pesticides and fertilizers may occasionally be limited (Egbe *et al*., 2013).

As stated by Khan *et al*. (2021), Bambara groundnut is a fast-growing plant that cannot withstand frosty environments at all stages in its growth, hence optimal growth are achieved in warm areas (Azam-Ali *et al*., 2001). Bambara groundnut can begin to flower at 30 days to 55 days from planting and last till the plant dies (Brink & Belay, 2006). Hardy Bambara groundnut is known to be a valuable source of nutrient-dense food when food is limited (Mbosso *et al*., 2020). This might be because of its climate-resilient traits, such its capacity to fix atmospheric nitrogen and to thrive in adverse conditions like barren soils and dry spell (Karunaratne *et al*., 2009). According to Chai *et al*. (2016), Bambara groundnut exhibits all the three drought resistance strategies, including tolerance, avoidance and escape. Despite water stress, the crop is remarkably resilient and stands out for its strong association between high seed production and good symbiotic nitrogen fixation capacity (Sambo, 2014). According to Kendabie *et al*. (2016), sandy-loam soil having a good drainage, pH between 5 and 6.5 and good tolerance to acidic and deficient soils is the optimum soil for growing Bambara groundnuts. An altitude of up to 1600 m above sea level and an average day temperature of 20 to 28℃ is suitable for Bambara groundnut cultivation (Basu *et al*., 2007).

2.4 Agro-morphological diversity of Bambara groundnut landraces

Owing to its diversity and localization in a variety of habitats, Bambara groundnut is becoming more and more significant in Africa South of Saharan (Olanrewaju *et al*., 2021). According to Gbaguidi *et al*. (2018) and Atoyebi *et al*. (2017), Bambara groundnut landraces exhibit a high level of variability for agro-morphological characters. The variations in characteristics among the landraces suggest that the chosen population has diversity that may be utilized in breeding initiatives (Olanrewaju *et al*.,

2021). Numerous crops, including sorghum (Jiang *et al*., 2020), rice (Rahman & Shah, 2019) and sweet potatoes (Ngailo *et al*., 2019), have shown evidence of the effects of genotype x environment interactions (GEIs). Crop growth and development have been observed to be impacted differently by various places and seasons (Mogale, 2018). For breeders, GEI is important in select the best genotypes that will perform well in specific environments (Olanrewaju *et al*., 2021). According to a study by Mogale (2018), distinct Bambara groundnut landraces responded differently to each variable in various places and years, proving the existence of GEI. Variations in the environment, soil fertility, and biotic variables have an impact on the plant genotypes studied across years in different places (Olanrewaju *et al*., 2021).

Production of Bambara groundnut is limited due to lack of improved cultural techniques (Anchirinah *et al*., 2001) and unprivileged effort to improve this crop (Lacroix *et al*., 2003). The average yield of Bambara groundnut is as low as 0.65 to 0.85 t ha^{-1} (Olukolu *et al.,* 2012) and 28.96 g $plant^{-1}$ (Chandra *et al*., 2017). Khan *et al*. (2021) revealed significant variation for all the agronomic traits except plant height among 15 Bambara groundnut studied. Valombola *et al*. (2019) reported high variation among accessions for yield and yield characters. The preference criteria for Bambara groundnut seeds, which are important for both cultivation and consumption, include several factors: taste and seed testa color, nutritional value and yield stability (Alake *et al*., 2015; Mayes *et al*., 2019; Tan *et al*., 2020).

2.5 Nutritional composition of Bambara groundnut seeds

Bambara groundnut is mainly farmed for human use and the remainder of the plant matter can be used to feed livestock (Anchirinah *et al*., 2001). In places with scarcity of protein of animal origin, the legume offers a significant supply of vital nutrients (Boye *et al*., 2010). Based on the findings of Ouedraogo *et al*. (2008) Bambara groundnut comprises 6.5% fat, 64.4% carbohydrates, 5.5% fiber and 23.6% protein. Amarteifio *et al*. (2006) reported minerals per mg/ 100g dry matter to be Ca (37 - 128), K (1545 - 2200), Mg (159 - 335), Na (16 - 25), P (313-563), and for the micro minerals (ppm) Cu (3.0 - 13.2), Fe (23.0 - 150) and Zn (13.9 - 77.0). The concentration of these minerals are greater than those in regularly eaten legumes, according to Halimi *et al*. (2019). Bambara groundnut is rich in lysine content but has lower levels of methionine, making it a good complementary protein source to grains, which are usually low in

lysine but high in methionine (Boye *et al*., 2010). In situations when animal protein sources are limited or prohibitively expensive, it can thereby satisfy the regular protein needs of marginal consumers (Boye *et al*., 2010).

The Bambara groundnut, coupled with other local sources of protein, can help undeveloped tropical countries address their nutritional problems (Massawe *et al*., 2005). When compared to the light seeded (cream) varieties, the dark seeded landraces (black and red) have the highest protein content (Nti, 2009). The iron content of red-seed varieties is almost two times that of cream seeds, therefore they are particularly useful in regions where there is an iron deficiency (Muimba-Kankolongo, 2018). However, Bambara groundnut lacks sulfur-containing proteins, similar to other legumes. It can be used to make a complete meal when combined with a staple crop like maize, which has more sulfur-containing amino acids (Vurayai *et al*., 2011).

2.6 Phytochemical composition of Bambara groundnuts

It has long been recognized that legumes contain significant amounts of phytochemicals including saponins, alkaloids, phenolics and other substances that can bind to dietary components and make them either partially and completely indigestible (Karunaratne *et al*., 2009). These phytochemicals may interfere with the functioning of certain human organs (Gemede & Ratta, 2014). According to Olaleye *et al*. (2013), the phytochemicals are primarily found in the testa of legumes. According to Margaret *et al*. (2019), the primary phytochemicals in Bambara groundnut are oxalate, phytate, trypsin inhibitor and tannins. Condensed tannins range from 0.0011 to 18.61 mg/g, trypsin inhibitor from 0.06 to 73.40 TI mg/g and phytic acid from 1.10 to 15.11 mg/g in different Bambara groundnut cultivars (Tan *et al*., 2020). Genetic, environmental, extractional, and analytical factors are all implicated in these variations (Duodu & Apea-Bah, 2017).

Numerous studies have found that the tannin content of various landraces grown by farmers varies greatly. According to Unigwe *et al*. (2018), mean condensed tannin concentrations per gram ranged from 0.20 to 6.20 mg. In accordance with prior studies, tannins, the primary anti-nutritional component of total polyphenols, account for over half of the phenol content in these seeds and directly correspond with seed-coat color (Sowndhararajan *et al*., 2011). Condensed tannins are more prevalent in the darker-colored seeds and are mostly found in the testa (Nti, 2009). According to Yao *et al*.

(2015), tannins in meals reduces the ability of proteins to be digested by either making them partially inaccessible or by preventing the action of digestive enzymes. Additionally, astringency and bitterness can be added to food by tannin molecules, which will make it less palatable (Rauf *et al*., 2019). According to Halimi *et al*. (2019), phytochemicals can lower the bioavailability of amino acids by as much as 50%. In accordance with Ndidi *et al*. (2014), different processing techniques as heat treatment (boiling and roasting), malting, soaking, fermentation and germination drastically lowered the phytochemicals in Bambara groundnut.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Description of the study sites

The study was conducted in three different areas in Embu County namely Ishiara, Kiamuringa and Kangaru (Figure 3.1). Ishiara is located in Embu County's Mbeere North Sub-County. Kiamuringa is located at Mbeere South Sub-County formerly known as Gachoka. Kangaru is located in Manyatta constituency in Embu West Sub-County. Bambara groundnut has not been previously cultivated in the selected study areas. Details of environmental conditions in the test sites are described in Table 3.1. Environmental conditions vary from one location to another and from season to season in the same location and their effects influence the crop yields.

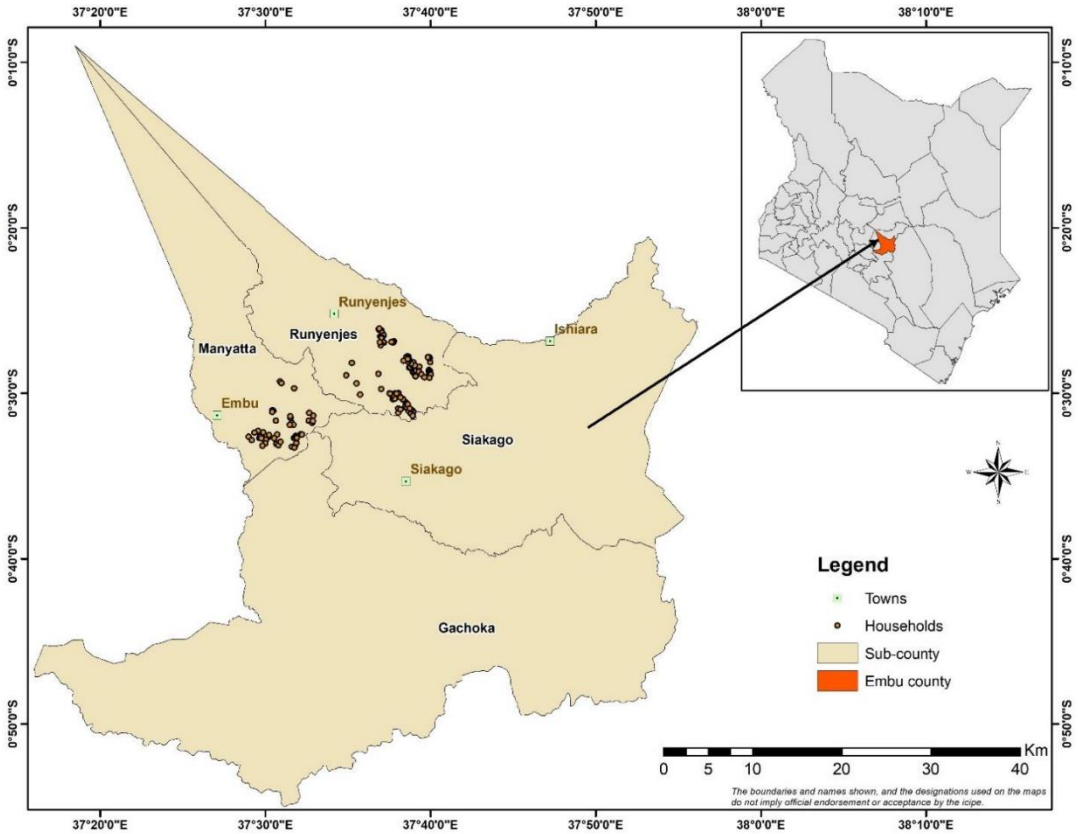

Figure 3.1: Map of study areas (Source: Wangithi *et al*., 2021)

Table 3.1: Biophysical characteristics of the three study sites

Location	Coordinates	Dominant soil type	Average Soil pH	Mean annual rainfall	Altitude (m asl)	Annual average temperature	Agro-eco zone	References
Ishiara, Mbeere North	-0.4530, 37.7888	Ferralsols and Acrisols	6.1	765 mm	840 m	24.9℃	Lower Midland 4	Kiarie *et al*., 2022; Jaetzold *et al*., 2006; Gachimbi, 2002
Kiamuringa, Mbeere South	-0.5719, 37.5361	Cambisols	6.1	800 mm	1143 m	21.6℃	Lower Midland 4	Jaetzold *et al*., 2006; Kiboi *et al*., 2021; Gachimbi, 2002
Kangaru, Embu West	-0.5150, 37.4564	Humic Nitisols	5.6	1230 mm	1496 m	19.6℃	Upper Midland 2	Jaetzold *et al*., 2006; Kiema *et al*., 2020; Gachimbi, 2002

3.2 Planting materials

Experimental plant materials were forty-five (45) landraces of Bambara groundnut collected at random from farmers in Bungoma, Kisumu, Kakamega, Busia and Vihiga Counties in Kenya (Table 3.2). The crop is well known and mainly cultivated in these counties by small holder farmers. The seeds were sorted according to the place of collection of the landraces. Codes were assigned to the different landraces for ease of identification.

Table 3.2: List of 45 Bambara groundnut used in this study

	Landraces	Source	Latitude	Longitude	Altitude (m a.s.l)	Annual rainfall (mm)	Mean Temp. (°C)	Dominating soil type	Total landraces	References
1	BG-109; BG-110; BG-111; BG-112; BG-125	Bungoma	0.6167° N	34.7667° E	1,523	400-1800	0-32	Lithosols	5	Machani *et al*., 2019; Mukwabi *et al*., 2019; Makilla, 2020
2	BS-101; BS-102; BS-103; BS-104; BS-105; BS-106; BS-107; BS-113; BS-114; BS-115; BS-129; BS-130; BS-131; BS-132; BS-133; BS-134; BS-141; BS-142; BS-143; BS-144; BS-145; BS-146; BS-147; BS-148	Busia	0.4600° N	34.1117° E	1,227	760-1750	21-23	Orthic Acrisols	24	Oria *et al*., 2021; Atsiaya *et al*., 2023
3	MU-139; MU-135; MU-137; MU-138; MU-140; MU-136	Kakamega	0.2827° N	34.7519° E	1,535	1250-1750	10-31	Ferralsols and Acrisols	6	Ochwang'i *et al*., 2014; Diwani *et al., 2013*
4	KS-108; KS-120; KS-116; KS-119; KS-117; KS-118	Kisumu	0.0917° S	34.7680° E	1,335	600-1630	18-34	sandy and clay	6	Ajuang *et al*., 2016; Oluoch *et al.*, 2017
5	LU-123; LU-122; LU-124; LU-121	Vihiga	0.0768° N	34.7078° E	1,500	950-1600	24-26	Acrisols and Cambisols	4	Caleb *et al*., 2022; Wild, 2022

3.3 Experimental design and layout

The study was conducted in the three sites described in section 3.1 above and laid out in Randomized Complete Block Design (RCBD) with 3 replicates. The study was carried out over two cropping seasons, that is, between April and August 2021 and between September 2021 and January 2022 across three study sites. Each experimental unit comprised of 10 plants. Plants were spaced 30 cm apart from one another in straight rows of 3 m each and the rows were spaced 1 m apart. The distance between each experimental plot was 2.0 meters. 45 Bambara groundnuts landraces were randomly allocated to the 45 experimental plots when planting. Two seeds per hole was sown at a depth of 3 cm and later thinned to one seedling two weeks after germination. The crops were rain fed throughout experimental period and no insecticide or herbicide was used. Di-ammonium phosphate (DAP) fertilizer was applied at the rate of 50 kg ha^{-1} at planting and mixed thoroughly with soil before the seeds were sown. Hand weeding was uniformly done twice at intervals of 3 weeks starting at the third week after planting. Harvesting was done after all the foliage in the plants had dried up which coincided with 15^{th} to 19^{th} week after planting. Mature pods were harvested manually by digging out the entire crop and picking the individual pods and thereafter sun-dried and threshed.

3.4 Data collection

3.4.1 Agro-morphological characterization

Five Bambara groundnut plants were randomly selected from each plot and then labelled for data collection. All the data were collected based on Bambara groundnuts descriptors (IPGRI, BAMNET, IITA, 2000) presented in Appendix 1. The qualitative characters evaluated were seed shape, stem hairiness, pod color, seed color, pod shape, terminal leaflet shape and pod texture. Phenological traits evaluated include number of days to physiological maturity, number of days to first flowering and number of days to 50% flowering. Growth components evaluated include plant height and tiller count per plant. After harvesting, the pods were then sun-dried and hand threshed after which the yield and yield components data was recorded. Yield and yield components were number of seeds per plant, number of pods per plant, weight of 100 seeds, seed width, yield and length of seeds.

3.4.2 Nutritional and phytochemical determination

Seventeen (17) most commonly consumed landraces were selected for analysis. These were: BS-104, KS-108, KS-116, BS-145, BS-148, BS-103, BG-114, BG-142, BG-125, BG-112, LU-123, MU-137, BS-141, BG-109, KS-118, LU-124 and BS-102. These landraces are the most popular among farmers and consumers because of the important characteristics such as seed colour, cooking ability and grain yields. Harvested seeds were manually cleaned, sorted, and checked for damage before being dry-milled into a fine powder using a high-speed universal disintegrator (FW 80-1). In accordance with the method described by Olaleye *et al*. (2013), the fine powder was maintained in airtight containers and kept cool and dry in the laboratory before being analysed. The biochemical and nutritional analysis was done in triplicates.

The Association of Official Analytical Chemists (AOAC) methods were used to determine proximate analysis for moisture (Appendix 2), total ash (Appendix 3) and crude fat (Appendix 5) as applied by Olayinka & Etejere (2018). The micro Kjeldahl method (Appendix 4) was used to determine crude protein by first quantifying the Nitrogen content and then multiplying it by 6.25 as described by Sáez-Plaza *et al*. (2013). The estimated values were then provided in g/100g. Quantification of tannin, flavonoid, saponin and alkaloid are detailed in Appendices 9, 10,11 and 12 following the procedures established by Wabali *et al*. (2020), Olaleye *et al.* (2013), Obadoni & Ochuko, (2001) and Dike *et al*. (2021) respectively.

Zinc and iron were determined using the methods outlined by FSSAI (2015) and Nerdy (2018) respectively. Potassium and sodium were determined using the Nerdy 2018 method. Zinc (Appendix 6) and iron (Appendix 7) were determined using atomic absorption spectrophotometry respectively while sodium and potassium were determine using flame photometry (Appendix 8). The standard curve was created using the readings of the standard concentrations versus absorbance then concentrations of sample solutions were determined.

3.5 Data analysis

Analysis of variance was performed on the agro-morphological data using the XLSTAT software version 2023 and Tukey's Honest Significant Difference (HSD) was employed to separate the means with a 95% significance level. Pearson correlation was to assess

the strength of linear relationship between quantitative agro-morphological variables. Principal component analysis was used to show an overview of the relationship between the quantitative traits and tested Bambara groundnut landraces. Clustering of studied Bambara groundnut landraces was done using Agglomerative Hierarchical Clustering (AHC). To determine genotype by environment (G x E) interactions under varying environmental conditions, analysis of variance was used to assess differences in genotypes and environments.

The phytochemical and nutritional data collected were subjected to analysis of variance (ANOVA) using XLSTAT software version 2022. The means that were significantly different were separated using Tukey's Honest Significant Difference (HSD) at 95% level of significance. Agglomerative Hierarchical Clustering (AHC) was used to conduct a cluster analysis in order to identify the diversity between the landraces in terms of their nutritional and biochemical makeup. Pearson correlation analysis was used to assess the strength of linear relationship between the nutritional and biochemical components.

CHAPTER FOUR

RESULTS

4.1 Agro-morphological diversity

4.1.1 Assessment of the qualitative traits

The qualitative traits assessed comprised of terminal leaflet shape, seed shape, pod texture, pod shape, seed colour, pod colour and stem hairiness (Table 4.1). All the qualitative characters that were evaluated showed variation, with the exception of the shape of the seeds, where all the landraces studied had oval shaped seeds. For terminal leaflet shape, 2% of landraces had lanceolate shape, 11% had rounded leaf shape while 87% had an oval leaf shape. Most landraces had brown pods (71%) while the rest (29%) had yellowish brown pods. Majority of the landraces (78%) had ovate-shaped pods while the rest (22%) had crescent-shaped pods. For pod texture, 80% of landraces were slightly grooved, 18% were much grooved, while 2% were smooth. The most variable qualitative attribute was the colour of the seeds varying from cream to dark brown, light red, dark purple, black, brownish red to dark brown (Plate 4.1). On their stems, 67% of the landraces exhibited scant hair, whereas 33% had dense hair. Figure 4.1 summarizes the frequency distribution of the 7 qualitative characters of the 45 Bambara groundnut landraces studied.

Plate 4.1: Variation in seed colour of Bambara groundnut landraces (a) black, (b) dark purple, (c) dark red, (d) dark brown, (e) light red, (f) reddish brown, (g) cream

Table 4.1: Qualitative traits of Bambara groundnut landraces

S/No.	Landrace	TLS*	Pod shape	Pod colour	Pod texture	Seed shape	Seed colour	Stem hairiness
1.	BG-109	Oval	Ovate	Brown	Slightly grooved	Oval	Cream	Sparse
2.	BG-110	Oval	Ovate	Yellowish brown	Slightly grooved	Oval	Cream	Sparse
3.	BG-111	Oval	Ovate	Brown	Slightly grooved	Oval	Cream	Sparse
4.	BG-112	Oval	Ovate	Brown	Slightly grooved	Oval	Cream	Dense
5.	BG-125	Oval	Ovate	Yellowish brown	Much grooved	Oval	Dark brown	Sparse
6.	BS-101	Oval	Ovate	Brown	Slightly grooved	Oval	Light red	Sparse
7.	BS-102	Oval	Ovate	Brown	Slightly grooved	Oval	Light red	Sparse
8.	BS-103	Oval	Ovate	Brown	Slightly grooved	Oval	Reddish brown	Dense
9.	BS-104	Oval	Ovate	Brown	Slightly grooved	Oval	Reddish brown	Sparse
10.	BS-105	Lanceolate	Ovate	Brown	Slightly grooved	Oval	Reddish brown	Dense
11.	BS-106	Oval	Ovate	Brown	Slightly grooved	Oval	Reddish brown	Sparse
12.	BS-107	Oval	Ovate	Brown	Slightly grooved	Oval	Light red	Sparse
13.	BS-113	Oval	Ovate	Brown	Slightly grooved	Oval	Dark brown	Dense
14.	BS-114	Oval	Ovate	Brown	Slightly grooved	Oval	Dark brown	Sparse
15.	BS-115	Oval	Ovate	Yellowish brown	Slightly grooved	Oval	Dark purple	Dense
16.	BS-129	Oval	Ovate	Yellowish brown	Slightly grooved	Oval	Dark purple	Sparse
17.	BS-130	Oval	Ovate	Brown	Slightly grooved	Oval	Black	Sparse
18.	BS-131	Oval	Ovate	Brown	Much grooved	Oval	Black	Sparse
19.	BS-132	Oval	Ovate	Brown	Slightly grooved	Oval	Black	Dense
20.	BS-133	Oval	Ovate	Brown	Slightly grooved	Oval	Dark purple	Dense
21.	BS-134	Oval	Crescent	Brown	Slightly grooved	Oval	Dark purple	Sparse
22.	BS-141	Oval	Ovate	Brown	Slightly grooved	Oval	Dark purple	Sparse
23.	BS-142	Oval	Ovate	Yellowish brown	Slightly grooved	Oval	Dark purple	Sparse
24.	BS-143	Oval	Ovate	Brown	Much grooved	Oval	Dark purple	Dense
25.	BS-144	Oval	Crescent	Yellowish brown	Much grooved	Oval	Black	Dense
26.	BS-145	Oval	Ovate	Brown	Slightly grooved	Oval	Black	Dense
27.	BS-146	Oval	Crescent	Yellowish brown	Slightly grooved	Oval	Black	Dense
28.	BS-147	Oval	Ovate	Brown	Slightly grooved	Oval	Black	Dense
29.	BS-148	Oval	Crescent	Yellowish brown	Slightly grooved	Oval	Black	Sparse
30.	KS-108	Oval	Crescent	Brown	Smooth	Oval	Reddish brown	Sparse
31.	KS-116	Oval	Ovate	Brown	Slightly grooved	Oval	Dark purple	Sparse

32.	KS-117	Oval	Ovate	Yellowish brown	Slightly grooved	Oval	Dark brown	Dense
33.	KS-118	Oval	Ovate	Brown	Slightly grooved	Oval	Dark purple	Sparse
34.	KS-119	Oval	Ovate	Brown	Slightly grooved	Oval	Dark brown	Sparse
35.	KS-120	Oval	Ovate	Brown	Slightly grooved	Oval	Dark purple	Sparse
36.	LU-121	Round	Ovate	Brown	Slightly grooved	Oval	Dark purple	Dense
37.	LU-122	Round	Crescent	Brown	Much grooved	Oval	Black	Dense
38.	LU-123	Round	Ovate	Brown	Much grooved	Oval	Dark purple	Sparse
39.	LU-124	Round	Ovate	Brown	Much grooved	Oval	Dark red	Sparse
40.	MU-135	Oval	Crescent	Yellowish brown	Slightly grooved	Oval	Dark red	Sparse
41.	MU-136	Oval	Crescent	Yellowish brown	Slightly grooved	Oval	Dark red	Sparse
42.	MU-137	Oval	Ovate	Yellowish brown	Much grooved	Oval	Reddish brown	Sparse
43.	MU-138	Oval	Ovate	Brown	Slightly grooved	Oval	Reddish brown	Sparse
44.	MU-139	Round	Crescent	Brown	Slightly grooved	Oval	Dark purple	Sparse
45.	MU-140	Oval	Crescent	Yellowish brown	Slightly grooved	Oval	Dark purple	Sparse

*TLS - terminal leaflet shape

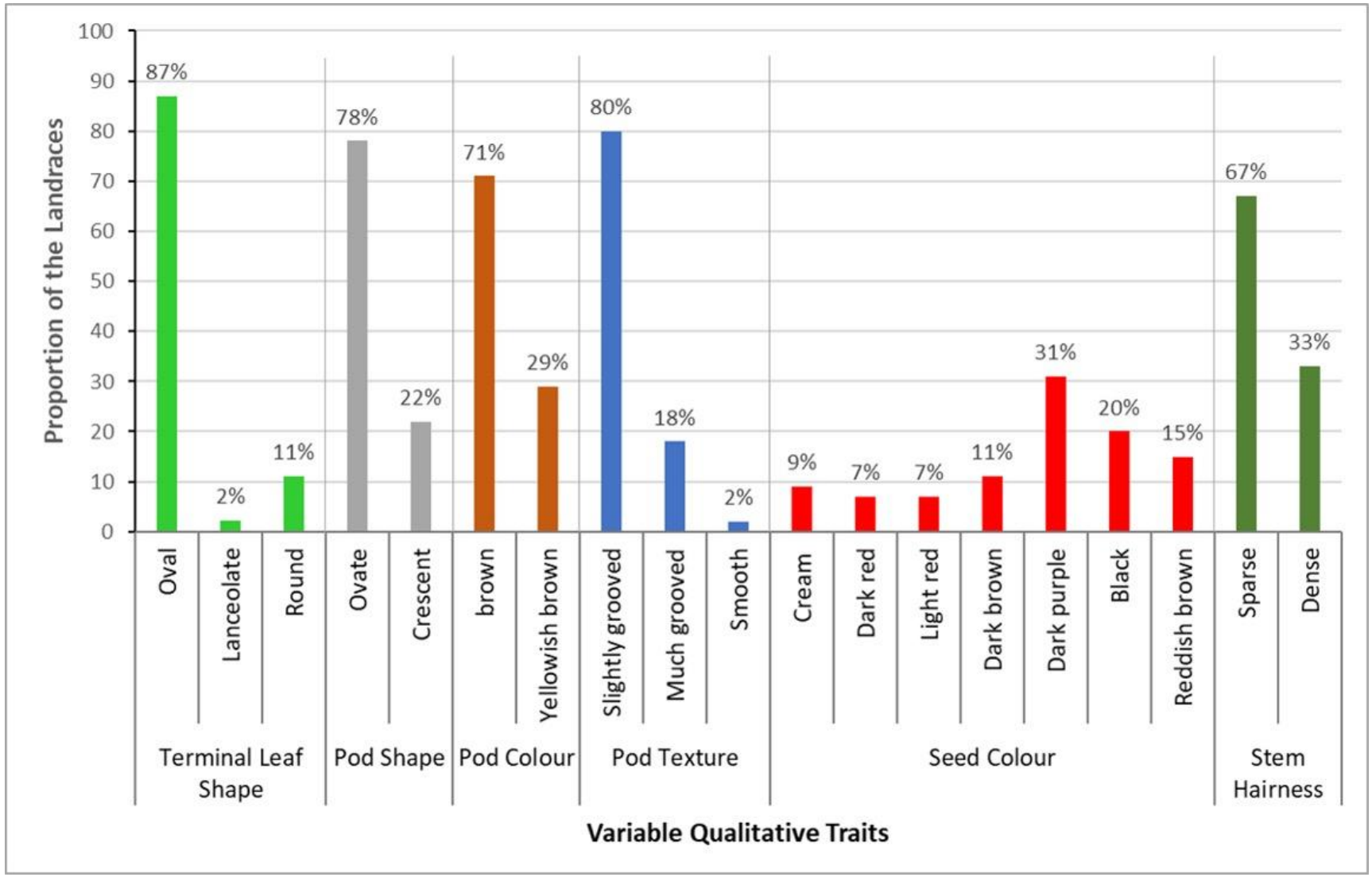

Figure 4.1: Frequency distribution in qualitative traits of the assessed Bambara groundnuts

4.1.2 Cluster analysis of Bambara groundnut landraces

Degree of differentiation between the assessed Bambara groundnut landraces was done using agglomerative hierarchical clustering (AHC) based on the qualitative and quantitative traits. The landraces were clustered into five distinct clusters based on 11 quantitative characters and 7 qualitative traits (Figure 4.2). The diversity between clusters was 77.40% while diversity within clusters was 22.60%. Cluster 1 had eight landraces from three different counties and within-cluster variance was 42.78%. Cluster 2 consisted of 5 landraces from two different counties namely Busia and Kisumu with 27.20% within-cluster variance. Cluster 3 recorded the highest number of landraces (20) from four different counties with 30.94% within-cluster variance. Cluster 4 had one landrace, BS-107 from Busia County. Cluster 5 contained eleven landraces from three different counties with the highest within-cluster variance (63.27%).

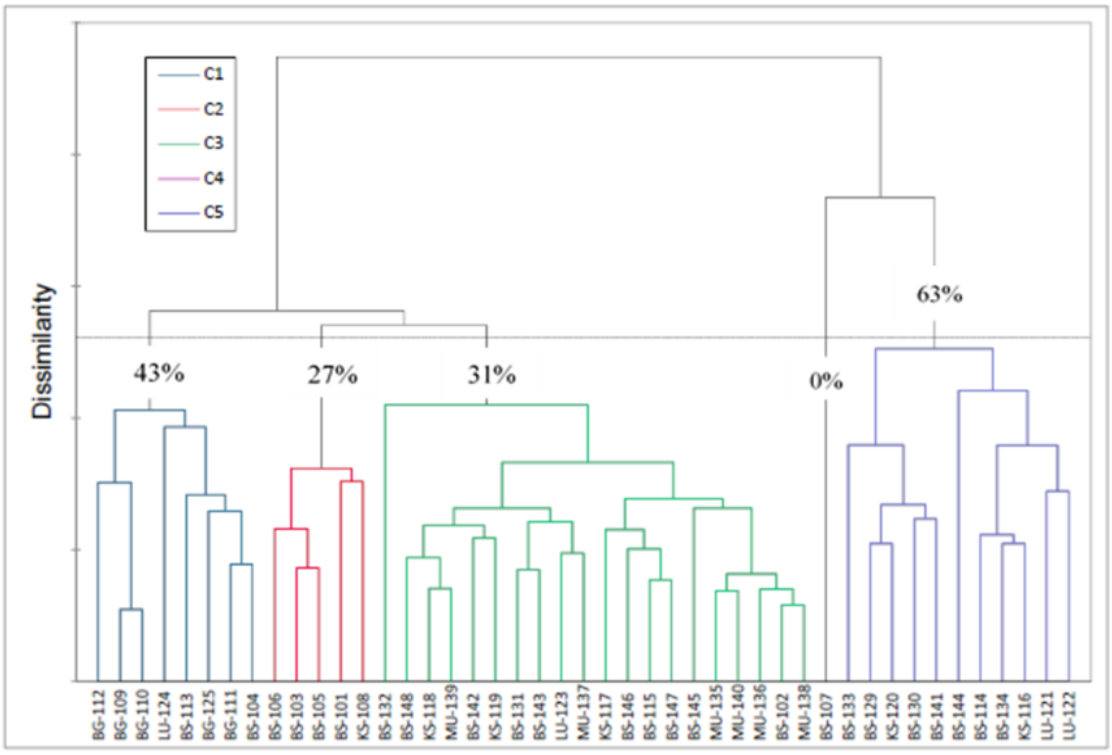

Figure 4.2: Dendrogram showing the agro-morphological diversity among the Bambara groundnut landraces

4.1.3 Principal component analysis using agro-morphological traits

Principal component analysis (PCA) was used to determine the association between tested Bambara groundnut landraces and the quantitative traits. Results of the PCA for the 45 Bambara groundnut accessions studied are presented in Table 4.2 and Figure 4.3.

The results revealed that the first four principal Components (PC1, PC2, PC3 and PC4) comprised a total of 70.65% of the total variations with the PC1, PC2, PC3 and PC4 explaining 27.64%, 20.59%, 12.53% and 9.89% of the total variation, respectively (Table 4.2). Number of seeds, days to 50% flowering, seed width and number of seeds made the most contribution to PC2 (31.70%), PC1 (26.22%), PC4 (36.02%) and PC3 (49.28%) respectively (Table 4.2 and Figure 4.3). Also, seed length, number of pods, yield, number of days to first flowering and plant height contributed significantly to the diversity of Bambara groundnut landraces. All other variables had little impact to the four principal factors.

Number of seeds, days to first flowering, number of pods and yield had a higher contribution in discriminating BS-129, KS-120, BS-107, LU-122, BS-144, BS-134, BS-114, KS-116 and LU-121 (Figure 4.3). Length of seeds, number of tillers, days to 50% flowering, plant height, days to maturity, seed width and weight of 100 seeds had higher impact on discriminating the landraces BG-110, BG-125, MU-136, BG-111, MU-138, LU-123, BG-109, LU-124, KS-108, BS-113 and BG-112 (Figure 4.3).

Table 4.2: Percentage contribution of agro-morphological traits of Bambara groundnut to the first four Principal Components of the PCA

Variables	PC1	PC2	PC3	PC4
Days to first flowering	20.554	0.142	0.270	0.731
Days to 50% flowering	26.215	2.543	0.546	0.367
Days to maturity	0.860	1.308	49.284	0.021
Plant height	4.972	8.479	0.710	24.930
No. of tillers	0.996	8.739	2.986	0.033
Seed length	1.723	22.695	0.627	13.662
Seed width	4.479	0.599	13.432	36.021
No. of pods	0.499	0.023	28.347	21.970
Weight of 100 seeds	19.661	2.170	3.356	1.901
No. of seeds	6.121	31.701	0.294	0.236
Yield t/ha	13.921	21.602	0.149	0.129
Eigenvalue	3.040	2.265	1.378	1.088
Variability (%)	27.638	20.593	12.528	9.894
Cumulative %	27.638	48.232	60.760	70.654

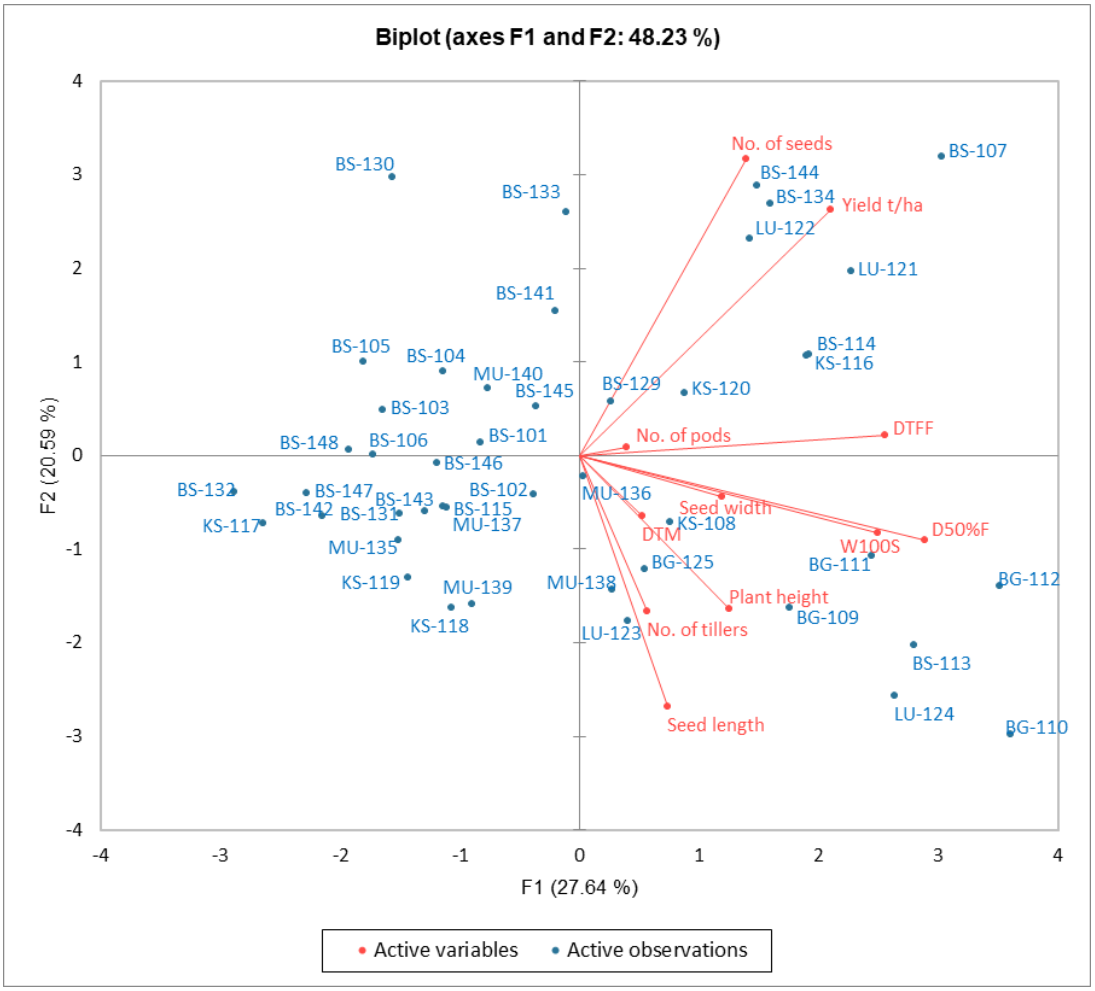

Figure 4.3: Principal quantitative agro-morphological components in the assessed Bambara groundnut landraces

4.1.4 Agronomic evaluation of Bambara groundnut landraces

4.1.4.1 Variation in growth and yield traits at Kangaru site

Analysis of variance revealed that there were no significant (P>0.05) variations in the phenological traits except for days to maturity (Table 4.3). Days to first flowering ranged between 51 and 53 days after planting; days to 50% flowering varied from 60 to 63 days after sowing; while days to maturity varied from 130 to 133 days after sowing. There were significant (P<0.05) seasonal variations for all the phenological traits that were evaluated with faster phenological changes being recorded in the first season except for days to 50% flowering (Table 4.3). Regarding the growth characteristics, the height of the plants and the quantity of tillers did not differ significantly (P>0.05). However, both the plant height and the number of tillers portrayed highly significant (P<0.0001) seasonal variations with higher values being

recorded in the second season for plant height and higher values of number of tillers were recorded in the first season (Table 4.3).

Additionally, ANOVA showed that all of the yield traits varied significantly ($P<0.05$) between the landraces (Table 4.3). A total of 31 pods were present in BS-105, while only 16 pods were present in BS-142. The landrace LU-124 had the longest seed length of 11.67 mm while BS-145 had the shortest seed length of 7.92 mm. While MU-137 had the lowest mean value of seed width at 7.11 mm, BS-144 had the greatest mean value of seed width at 9.78 mm. Weight of 100 seeds ranged between 32.86 g and 59.10 g in BS-132 and BG-109 respectively. The most seeds per plant were found in BS-107 with 56, while the fewest seeds per plant were found in BS-142 with 16. With a yield of 2.44 t ha^{-1}, the landrace BS-144 had the highest value, whereas BS-142 had the lowest value (0.60 t ha^{-1}). (Table 4.3). All yield components showed statistically significant ($P<0.05$) to extremely significant ($P<0.0001$) seasonal variations, with decreased yield values being observed in the second season (Table 4.3).

Table 4.3: Variation in growth and yield traits of Bambara groundnut landraces at Kangaru site

No.	Landrace	DTFF	D50%F	Days to Maturity	Plant height (cm)	No. of tillers	Number of pods/plant	Seed length (mm)	Seed width (mm)	Weight of 100 Seeds (g)	Number of seeds	Yield (t/ha)
1.	BG-110	52.67	61.83	133.33	24.03	24.24	28.05 a-c	10.53 b-e	8.44 f-m	53.71 a-c	28.05 d-l	1.67 a-i
2.	BG-112	53.33	62.83	131.67	23.49	21.53	29.46 ab	10.82 bc	9.14 b-d	54.41 ab	29.59 d-l	1.78 a-h
3.	BS-113	53.00	61.67	131.33	23.66	23.98	26.70 a-c	11.03 ab	9.09 b-e	50.93 a-c	26.70 f-l	1.45 a-i
4.	BG-109	51.83	61.00	132.67	24.26	22.75	27.48 a-c	10.10 d-h	9.10 b-e	59.10 a	27.48 e-l	1.81 a-g
5.	LU-124	53.17	62.00	133.67	20.17	24.71	21.89 a-c	11.67 a	8.82 c-i	48.75 a-c	21.87 i-l	1.09 c-i
6.	BS-114	53.17	61.83	131.67	22.61	23.64	20.17 a-c	8.96 l-q	9.24 a-c	44.29 a-c	40.34 a-g	1.79 a-h
7.	KS-108	52.00	61.17	132.33	22.39	23.83	29.57 ab	9.59 g-l	8.91 b-g	45.11 a-c	29.46 d-l	1.37 a-i
8.	KS-116	52.00	61.17	133.67	21.69	23.70	22.11 a-c	8.32 q-t	8.65 c-j	44.31 a-c	44.21 a-d	2.06 a-c
9.	BS-144	52.83	60.83	132.33	20.95	21.97	24.74 a-c	9.14 j-o	9.78 a	45.53 a-c	49.47 ab	2.44 a
10.	BG-111	52.50	61.33	132.67	22.61	20.77	25.14 a-c	10.02 d-h	8.21 i-q	49.46 a-c	25.14 f-l	1.32 a-i
11.	BS-134	53.00	61.17	132.67	21.69	20.48	21.91 a-c	9.05 k-p	9.50 ab	38.45 a-c	43.81 a-e	1.91 a-f
12.	BS-107	53.00	61.83	131.67	22.79	21.22	28.19 a-c	8.46 p-t	8.21 i-q	34.43 bc	56.38 a	2.02 a-e
13.	LU-121	52.33	61.17	131.67	21.20	21.99	23.43 a-c	9.15 j-o	8.35 f-p	49.65 a-c	46.87 a-c	2.40 ab
14.	LU-122	52.17	61.00	132.67	22.07	22.08	19.99 a-c	9.11 k-p	7.89 l-s	50.96 a-c	39.98 a-g	2.05 a-d
15.	BS-101	52.00	60.83	131.33	20.12	24.57	31.06 a	10.81 bc	8.66 c-j	39.46 a-c	31.06 c-l	1.26 c-i
16.	BG-125	52.17	61.00	133.67	20.76	23.47	22.56 a-c	10.61 b-d	8.28 h-p	42.35 a-c	23.06 h-l	0.98 c-i
17.	LU-123	52.33	61.17	133.00	22.09	24.09	19.17 a-c	10.65 b-d	8.36 f-o	42.28 a-c	19.17 j-l	0.81 f-i
18.	MU-138	52.17	61.00	133.00	22.55	24.10	22.39 a-c	9.50 h-m	7.87 m-s	40.36 a-c	22.42 i-l	0.93 d-i
19.	MU-135	52.00	60.83	132.67	22.67	22.40	22.38 a-c	10.83 bc	8.66 c-j	38.89 a-c	22.33 i-l	0.89 e-i
20.	MU-136	52.33	61.00	132.00	22.66	22.70	23.37 a-c	8.86 m-s	8.95 b-f	39.74 a-c	23.33 h-l	0.94 c-i
21.	BS-102	52.50	61.17	131.67	21.81	22.30	25.38 a-c	9.10 d-h	8.42 f-n	37.67 bc	25.38 f-l	1.00 c-i
22.	BS-131	52.83	61.17	132.00	22.11	21.63	21.72 a-c	10.22 c-g	8.41 f-o	41.56 a-c	21.72 i-l	1.03 c-i
23.	BS-129	52.83	61.17	131.33	22.36	23.96	21.16 a-c	8.22 r-t	7.74 p-s	38.60 a-c	34.35 b-k	1.62 a-i
24.	BS-105	52.17	60.83	132.33	22.45	23.13	31.10 a	7.97 t	7.96 k-s	36.45 bc	31.10 c-l	1.24 c-i
25.	KS-120	52.17	61.00	132.67	22.11	21.36	18.84 a-c	8.90 l-r	8.84 c-h	37.26 bc	37.67 b-i	1.43 a-i
26.	BS-103	52.00	60.67	133.00	21.90	22.10	27.08 a-c	8.99 l-q	7.56 r-t	41.79 a-c	27.08 f-l	1.18 c-i
27.	BS-145	53.17	61.17	132.67	21.56	21.09	23.79 a-c	7.92 t	7.11 t	42.87 a-c	23.87 g-l	1.11 c-i
28.	KS-118	51.50	60.67	133.00	22.56	22.61	21.23 a-c	9.72 f-k	7.81 o-s	44.96 a-c	21.11 i-l	1.00 c-i
29.	MU-140	52.83	61.33	132.33	22.10	20.76	21.23 a-c	9.04 k-p	8.16 j-r	43.91 a-c	21.26 i-l	0.93 d-i
30.	BS-130	52.00	60.33	133.67	21.55	20.91	19.51 a-c	8.53 o-t	8.73 c-j	38.99 a-c	39.02 b-h	1.56 a-i
31.	BS-115	52.33	61.00	132.50	22.40	21.87	21.86 a-c	9.54 g-m	7.65 q-t	39.26 a-c	21.86 i-l	0.93 c-i
32.	MU-139	52.17	61.00	132.67	22.07	24.07	19.37 a-c	9.80 f-j	7.85 m-s	40.03 a-c	19.32 j-l	0.81 f-i
33.	BS-146	52.67	60.67	132.33	21.42	20.30	24.71 a-c	10.01 d-h	8.50 e-l	34.65 bc	24.73 f-l	0.94 c-i

34.	BS-106	51.33	59.83	131.67	22.48	23.09	29.84 ab	9.29 i-n	7.87 m-s	33.37 bc	29.84 d-l	1.04 c-i
35.	BS-141	52.50	60.50	132.33	21.77	21.22	17.53 bc	8.76 n-s	8.53 d-k	36.76 bc	35.09 b-j	1.29 b-i
36.	BS-147	51.83	59.83	132.00	21.08	23.41	22.36 a-c	10.33 c-f	8.37 f-o	39.96 a-c	22.36 i-l	0.94 c-i
37.	BS-104	51.83	60.50	132.00	21.91	21.29	27.00 a-c	8.78 n-s	7.37 st	44.24 a-c	27.00 f-l	1.17 c-i
38.	BS-143	52.17	60.17	132.33	21.22	21.76	21.48 a-c	10.09 d-h	8.42 f-o	41.07 a-c	21.41 i-l	0.95 c-i
39.	KS-119	52.33	61.17	133.00	21.50	22.75	18.26 a-c	10.01 d-h	8.15 j-r	34.69 bc	18.26 kl	0.66 hi
40.	KS-117	51.00	60.17	132.67	21.57	22.07	23.11 a-c	10.31 c-f	8.30 g-p	34.94 bc	23.11 h-l	0.81 f-i
41.	BS-148	52.50	60.50	133.00	20.97	20.97	20.57 a-c	9.88 e-i	8.46 f-m	36.91 bc	20.57 j-l	0.80 f-i
42.	BS-133	51.67	60.00	131.33	20.06	22.88	20.42 a-c	8.21 st	8.53 d-k	34.98 bc	40.85 a-f	1.47 a-i
43.	MU-137	52.17	61.00	133.33	21.84	21.83	19.89 a-c	8.86 m-s	7.41 st	34.70 bc	19.83 j-l	0.74 g-i
44.	BS-132	51.67	60.00	132.50	21.57	23.28	21.73 a-c	8.98 l-q	7.82 n-s	32.86 c	21.73 i-l	0.88 f-i
45.	BS-142	52.50	60.50	131.33	20.77	21.68	16.01 c	10.60 b-d	8.28 h-p	37.86 bc	16.05 l	0.60 i
P Value		<0.0001	0.723	0.640	0.070	0.251	<0.0001	0.251	<0.0001	<0.0001	<0.0001	<0.0001
Standard Error		0.021	0.559	0.619	0.783	0.915	2.276	0.021	0.109	3.734	2.921	0.200
Season 1		52.08 b	61.55 a	131.41 b	21.47 b	22.89 a	27.28 a	10.10 a	8.85 a	53.09 a	34.00 a	1.81 a
Season 2		52.57 a	60.36 b	133.45 a	22.43 a	22.03 b	19.17 b	9.02 b	7.88 b	30.13 b	23.57 b	0.72 b
P Value		<0.0001	0.004	<0.0001	<0.0001	<0.0001	<0.0001	0.002	<0.0001	<0.0001	<0.0001	<0.0001
Standard Error		0.118	0.131	0.090	0.165	0.193	0.480	0.025	0.023	0.787	0.616	0.042

Key: Means followed by the same letter are not significantly different based on Tukey's Honest Significant Difference (HSD) at α = 0.05. DTFF = days to first flowering, D50%F = days to 50% flowering, DTM = Days to maturity

4.1.4.2 Variation in growth and yield traits at Ishiara site

According to analysis of variance (ANOVA), the Bambara groundnut landraces reported highly significant ($P<0.0001$) variation in days to first flowering and days to maturity but not in days to 50% flowering, as shown in Table 4.4. In regards to days to first flowering, KS-119 took the shortest time of 50 days while BS-133 took the longest period of 54 days after sowing. Days to 50% flowering varied between 58 days to 62 days (Table 4.4). Days to maturity ranged between 130 to 132 days after sowing in BS-147 and MU-139 respectively. There were extremely significant ($P<0.001$) seasonal variations in the three phenological variables that were assessed with fast phenological changes being observed in the second season except for days to maturity (Table 4.4). For the growth variables, plant height and number of tillers did not differ significantly ($P>0.05$) (Table 4.4). Plant height varied between 24.02 cm and 13.17 cm while number of tillers ranged from 19 to 26. The plant height recorded highly significant ($P<0.0001$) seasonal variation with season 1 recording higher plant height values. The number of tillers varied significantly by season ($P<0.05$), with the first cropping season having the highest number of tillers (Table 4.4).

The study further assessed the variation in the yield components including the number of seeds per plant, average seed width (mm), number of pods per plant, weight of 100 seeds (g), average seed length (mm) and the computed yield (t/ha) as displayed in Table 4.4. There was highly significant ($P<0.0001$) variation between the landraces for all yield traits except the seed length. LU-121 had the fewest pods (19), whereas BS-101 had the most pods (55). The landrace KS-118 had the longest seed length of 13.32 mm while LU-122 had the shortest seed length with 7.08 mm. While MU-137 had the lowest mean value of seed width at 7.48 mm, BS-144 had the greatest mean value of seed width at 9.49 mm. Weight of hundred seeds ranged between 24.60 g and 58.70 g in BS-132 and BG-112 respectively. The most seeds, 62, were found in BS-144, and the least, 20, were found in LU-124. In terms of yield, the landrace BS-114 had the highest value (3.16 t ha^{-1}), while BS-132 had the lowest value (0.69 t ha^{-1}). With the exception of seed length, all yield parameters showed highly significant ($P<0.001$) seasonal variation, with lower yield values noted in the second season (Table 4.4).

Table 4.4: Variation in growth and yield traits of Bambara groundnut landraces at Ishiara site

No.	Landrace	DTFF	D50%F	Days to Maturity	Plant height (cm)	Number of tillers	Number of pods	Seed length (mm)	Seed width (mm)	Weight of 100 Seeds (g)	Number of seeds	Yield (t/ha)
1.	BG-110	51.67 a-c	60.83	132.00 a-c	30.17	26.06	26.03 b-d	12.31	8.72 a-j	54.67 ab	25.78 k	1.48 c-h
2.	BG-111	53.00 a-c	62.00	131.33 a-c	26.75	22.22	32.44 b-d	12.38	8.88 a-i	52.25 a-c	32.44 h-k	1.82 b-h
3.	KS-116	52.67 a-c	61.17	132.33 a-c	26.61	24.11	27.29 b-d	11.14	8.08 g-n	45.25 a-f	55.61 a-e	2.50 a-d
4.	MU-138	52.33 a-c	61.33	132.67 ab	29.88	23.81	36.71 b	10.18	8.36 b-n	35.80 b-g	36.71 e-k	1.43 c-h
5.	BS-113	54.00 ab	61.50	132.00 a-c	26.36	25.31	27.82 b-d	12.30	8.69 a-k	47.75 a-e	27.82 k	1.32 c-h
6.	BS-114	50.33 bc	59.00	132.33 a-c	26.81	23.87	28.83 b-d	12.05	9.11 a-f	51.85 a-c	57.66 a-d	3.16 a
7.	BS-106	52.67 a-c	60.67	131.33 a-c	27.84	24.40	36.25 bc	10.82	8.43 b-n	37.80 b-g	36.25 e-k	1.44 c-h
8.	BG-112	51.33 a-c	60.33	131.67 a-c	27.36	23.01	31.84 b-d	11.49	8.69 a-k	58.70 a	31.84 h-k	1.93 a-h
9.	KS-108	52.00 a-c	60.83	132.00 a-c	25.76	25.56	32.18 b-d	10.87	8.57 a-m	41.77 a-g	32.18 h-k	1.32 c-h
10.	BG-125	52.33 a-c	60.83	132.67 ab	27.62	25.22	29.99 b-d	10.30	7.80 j-n	40.04 a-g	29.99 i-k	1.20 e-h
11.	BS-101	51.33 a-c	59.33	132.00 a-c	26.16	25.56	55.27 a	10.38	8.36 b-n	38.73 a-g	55.27 a-f	2.17 a-e
12.	BS-107	52.67 a-c	60.67	131.67 a-c	25.80	21.22	30.29 b-d	10.74	8.60 a-m	44.64 a-g	60.59 ab	2.93 ab
13.	BS-133	54.17 a	61.83	131.00 a-c	27.64	24.78	27.29 b-d	9.42	8.21 d-n	32.36 c-g	54.58 a-g	1.92 a-h
14.	KS-120	53.00 a-c	61.17	131.67 a-c	25.97	20.04	26.00 b-d	12.99	8.12 f-n	39.34 a-g	51.99 a-h	2.08 a-f
15.	LU-121	52.33 a-c	61.17	132.00 a-c	25.88	23.19	19.59 d	13.07	7.61 mn	50.47 a-d	39.17 c-k	2.06 a-g
16.	BS-144	51.33 a-c	59.00	132.00 a-c	26.62	22.26	31.27 b-d	8.28	9.09 a-g	38.00 b-g	62.54 a	2.53 a-c
17.	LU-122	52.33 a-c	60.83	132.00 a-c	26.65	23.06	24.78 b-d	7.08	7.77 j-n	51.96 a-c	49.55 a-i	2.51 a-c
18.	BS-143	51.67 a-c	59.33	131.67 a-c	27.91	23.96	27.87 b-d	10.15	8.91 a-i	38.59 a-g	27.87 k	1.17 e-h
19.	BS-104	51.67 a-c	59.67	131.67 a-c	27.69	21.46	34.70 b-d	9.93	7.80 j-n	45.77 a-f	34.70 f-k	1.60 c-h
20.	BS-141	52.67 a-c	60.50	131.33 a-c	29.63	22.50	29.35 b-d	9.53	7.72 k-n	27.67 e-g	58.69 a-c	1.73 b-h
21.	LU-124	52.00 a-c	60.67	131.33 a-c	26.27	26.46	20.93 cd	11.70	9.30 ab	45.95 a-f	20.93 k	0.99 e-h
22.	BG-109	51.33 a-c	60.33	131.67 a-c	26.76	21.55	29.92 b-d	10.17	7.96 i-n	55.36 ab	29.92 i-k	1.73 b-h
23.	BS-129	51.00 a-c	59.17	131.67 a-c	28.45	24.38	23.75 b-d	10.30	8.88 a-i	31.74 c-g	39.46 c-k	1.40 c-h
24.	BS-103	50.83 a-c	58.67	131.00 a-c	28.49	24.29	37.39 b	9.95	7.99 h-n	38.86 a-g	37.39 d-k	1.55 c-h
25.	KS-119	50.00 c	58.83	132.00 a-c	26.67	24.11	27.47 b-d	13.00	8.66 a-l	42.37 a-g	27.47 k	1.20 e-h
26.	KS-118	51.67 a-c	60.00	131.67 a-c	26.75	23.57	22.79 b-d	13.32	8.97 a-h	35.98 b-g	22.79 k	0.83 gh
27.	MU-135	50.17 c	59.00	132.33 a-c	27.78	22.03	27.72 b-d	10.67	9.19 a-d	32.50 c-g	27.72 k	1.02 e-h
28.	MU-139	51.00 a-c	59.67	133.00 a	27.79	25.62	24.17 b-d	10.12	8.64 a-l	31.66 c-g	24.17 k	0.81 h
29.	KS-117	51.33 a-c	60.00	131.67 a-c	25.96	23.34	25.69 b-d	13.14	8.45 b-n	38.95 a-g	25.69 k	1.07 e-h
30.	MU-136	51.00 a-c	59.83	131.00 a-c	26.78	23.85	28.82 b-d	9.45	9.49 a	34.98 b-g	28.57 jk	1.15 e-h
31.	BS-148	50.33 bc	58.17	132.33 a-c	26.19	19.94	30.48 b-d	10.21	8.30 c-n	45.11 a-g	30.48 i-k	1.54 c-h
32.	BS-147	50.67 a-c	58.50	130.33 c	26.68	24.97	30.89 b-d	10.44	8.64 a-l	33.53 c-g	30.70 i-k	1.18 e-h
33.	BS-145	51.00 a-c	58.67	131.17 a-c	27.67	23.44	29.76 b-d	9.97	8.46 b-n	37.36 b-g	29.76 i-k	1.26 d-h

34.	BS-146	51.00 a-c	58.67	131.67 a-c	28.31	19.78	26.30 b-d	10.53	9.13 a-e	36.78 b-g	26.30 k	1.09 e-h
35.	BS-115	51.67 a-c	59.50	130.67 bc	26.71	22.08	27.51 b-d	12.10	7.91 i-n	39.76 a-g	27.39 k	1.13 e-h
36.	BS-105	51.00 a-c	58.67	131.33 a-c	26.52	24.66	33.90 b-d	8.64	7.68 l-n	36.15 b-g	33.90 g-k	1.30 c-h
37.	MU-140	50.33 bc	59.50	132.33 a-c	27.93	22.85	25.51 b-d	8.13	8.87 a-i	32.54 c-g	25.51 k	0.86 f-h
38.	BS-102	52.33 a-c	60.33	132.00 a-c	24.02	23.08	25.65 b-d	10.21	8.18 e-n	31.79 c-g	25.65 k	0.81 h
39.	LU-123	52.67 a-c	60.83	131.00 a-c	26.26	23.57	23.13 b-d	9.61	7.86 j-n	42.17 a-g	23.13 k	1.00 e-h
40.	BS-132	51.33 a-c	59.17	130.67 bc	28.63	24.22	25.48 b-d	8.76	9.27 -bc	24.60 g	25.48 k	0.69 h
41.	BS-142	50.33 bc	58.17	131.33 a-c	27.98	19.83	27.83 b-d	10.53	8.71 a-k	32.01 c-g	27.82 k	0.94 e-h
42.	BS-134	51.00 a-c	59.17	132.00 a-c	26.97	22.32	20.50 d	8.45	8.06 h-n	26.35 fg	41.00 b-k	1.14 e-h
43.	BS-130	50.33 bc	58.17	131.33 a-c	27.58	21.78	24.34 b-d	7.40	7.66 l-n	32.91 c-g	48.68 a-j	1.68 c-h
44.	MU-137	51.67 a-c	60.17	131.67 a-c	27.78	22.06	23.11 b-d	9.40	7.48 n	28.47 e-g	23.11 k	0.76 h
45.	BS-131	50.33 bc	58.00	132.00 a-c	27.51	22.02	23.23 b-d	10.12	8.41 b-n	29.86 d-g	23.23 k	0.77 h
P Value		<0.0001	0.953	<0.0001	0.325	0.093	<0.0001	0.085	<0.0001	<0.0001	<0.0001	<0.0001
Standard Error		0.667	0.882	0.360	1.106	1.383	2.707	1.304	0.177	3.632	3.648	0.218
Season 1		51.92 a	60.61 a	130.73 b	30.05 a	23.75 a	35.62 a	10.16	8.83 a	47.32 a	44.55 a	2.12 a
Season 2		51.27 b	59.12 b	132.67 a	24.33 b	22.80 b	21.36 b	10.80	8.05 b	31.40 b	26.00 b	0.84 b
P Value		0.001	<0.0001	<0.0001	<0.0001	0.022	<0.0001	0.101	<0.0001	<0.0001	<0.0001	<0.0001
Standard Error		0.141	0.186	0.076	0.233	0.291	0.571	0.275	0.037	0.776	0.769	0.046

Key: Means followed by the same letter are not significantly different based on Tukey's Honest Significant Difference (HSD) at α = 0.05. DTFF = Days to first flowering, D50%F = Days to 50% flowering, DTM = Days to maturity

4.1.4.3 Variation in growth and yield traits at Kiamuringa site

Days to first flowering and days to 50% flowering did not differ significantly ($P>0.05$) between Bambara groundnut landraces, while days to maturity had significant ($P<0.0001$) differences between the landraces (Table 4.5). Days to first flowering ranged from 50 to 53 days after sowing while days to 50% flowering varied between 59 and 62 days after planting. Days to maturity ranged between 129 days recorded by MU-140 and 132 days for BG-125. Seasonal variations were highly significant ($P<0.0001$) for days to maturity and days to first flowering and significant ($P<0.05$) for days to 50% flowering (Table 4.5). Faster phenological changes were observed in season 1. For the growth variables, there were no significant ($P>0.05$) differences in both the plant height which ranged from 21.67 to 26.31 cm and the number of tillers which ranged from 19 to 25. The plant height also portrayed highly significant ($P<0.0001$) seasonal variations with season 1 recording higher values than in season 2. As for the number of tillers, there was no seasonal variations (Table 4.5).

For all of the yield parameters examined, analysis of variance (ANOVA) further showed high significant ($P<0.0001$) variations among the analysed Bambara groundnut landraces (Table 4.5). Number of pods was highest in KS-108 with 34 and lowest in BS-141 with 17. The highest seed length of 11.85 mm was observed in landrace LU-124 while landrace MU-140 had the lowest seed length of 8.03 mm. The landrace BS-103 recorded the lowest mean value of seed width at 7.40 mm, while BS-134 displayed the highest mean value of seed width at 9.41 mm. Weight of 100 seeds was greater (77.26 g) in landrace BS-134 and lower (35.02 g) in landrace BS-146. BS-134 recorded the highest number of seed with 67 while BS-132 recorded the lowest number of seeds with 18. The landrace BS-134 performed significantly better in terms of yield attaining 5.01 t ha^{-1} while BS-132 attained the least yield of 0.84 t ha^{-1} (Table 4.5). In terms of seasons, all the yield components showed highly significant ($P<0.0001$) differences with lower yield values being recorded in the cropping second season (Table 4.5).

Table 4.5: Variation in growth and yield traits of Bambara groundnut landraces at Kiamuringa site

No.	Landrace	DTFF	D50%F	DTM	Plant height (cm)	No. of tillers	No. of pods	Seed length (mm)	Seed width (mm)	Weight of 100 seed (g)	No. of seeds	Yield (t/ha)
1.	LU-124	53.17	62.17	130.67 a-c	25.06	23.69	29.68 a-d	11.85 a	8.96 a-e	57.82 a-d	29.59 g-k	1.88 c-i
2.	BG-112	53.17	62.50	130.67 a-c	25.36	20.34	28.60 a-d	10.95 a-c	9.08 a-c	46.80 b-d	28.66 h-k	1.50 e-i
3.	BS-107	53.17	62.00	130.67 a-c	23.83	21.90	33.61 ab	9.65 c-m	8.40 b-i	43.66 b-d	67.27 a	3.27 bc
4.	BG-110	52.83	62.17	130.00 a-c	25.14	23.29	25.33 a-d	10.74 a-d	8.52 b-i	61.51 a-c	25.32 h-k	1.92 c-i
5.	BS-134	52.83	61.33	131.00 a-c	22.75	19.67	27.80 a-d	9.76 b-l	9.41 a	77.26 a	55.04 a-c	5.01 a
6.	MU-136	52.33	61.33	131.00 a-c	24.57	22.16	32.45 a-c	8.88 i-o	8.89 a-f	50.90 b-d	32.96 e-k	1.95 c-i
7.	BG-109	52.17	61.50	131.00 a-c	26.31	24.03	21.97 a-d	10.15 b-i	9.12 ab	52.38 b-d	21.89 jk	1.27 e-i
8.	BS-129	52.83	61.33	130.33 a-c	23.93	23.77	25.96 a-d	9.69 c-m	8.29 b-j	45.86 b-d	43.29 c-h	2.49 b-f
9.	BG-125	52.17	61.17	132.00 a	23.92	21.71	30.10 a-d	10.46 b-g	8.19 d-l	49.92 b-d	30.14 g-k	1.61 d-i
10.	KS-108	52.00	61.33	131.00 a-c	24.51	22.71	34.71 a	9.78 b-l	8.72 a-g	41.13 cd	34.67 d-k	1.50 e-i
11.	BG-111	52.67	62.00	131.33 a-c	25.36	19.45	27.68 a-d	10.45 b-g	8.71 a-g	41.25 b-d	27.33 h-k	1.27 e-i
12.	LU-121	52.33	61.33	131.67 b	23.23	21.28	33.02 a-c	9.29 f-o	7.94 g-l	49.97 b-d	66.00 ab	3.60 ab
13.	BS-144	53.00	61.50	130.33 a-c	24.66	22.02	23.96 a-d	8.28 no	9.02 a-d	43.74 b-d	47.88 b-g	2.36 b-g
14.	LU-123	52.33	61.33	130.33 a-c	25.06	25.54	24.73 a-d	10.66 a-e	8.32 b-j	46.63 b-d	24.77 h-k	1.24 f-i
15.	KS-116	52.50	61.50	132.00 a	23.54	23.78	21.10 a-d	8.98 i-o	8.21 d-l	41.08 cd	42.36 c-i	1.94 c-i
16.	BS-114	53.33	61.67	129.67 bc	22.87	23.93	19.82 cd	8.68 k-o	8.88 a-f	44.99 b-d	39.56 c-j	2.00 c-i
17.	BS-113	52.67	61.50	129.67 bc	24.48	22.85	24.34 a-d	10.50 b-f	8.66 a-h	43.87 b-d	24.34 i-k	1.15 f-i
18.	BS-145	53.17	61.83	131. 0 a-c	23.70	19.35	26.13 a-d	9.02 h-o	7.78 i-l	51.21 b-d	27.85 h-k	1.57 d-i
19.	MU-135	51.83	60.83	131.0 a-c	22.44	22.56	28.35 a-d	10.36 b-g	8.45 b-i	44.20 b-d	31.20 f-k	1.47 e-i
20.	LU-122	51.67	60.67	131.33 a-c	23.34	21.81	24.93 a-d	9.19 g-o	7.72 i-l	54.86 a-d	49.72 a-f	2.96 b-d
21.	BS-142	52.83	61.50	130.67 a-c	23.09	24.13	23.24 a-d	10.47 b-g	8.28 b-k	39.35 cd	24.28 i-k	1.02 g-i
22.	KS-120	52.00	61.00	130.33 a-c	25.09	23.47	18.18 d	9.52 d-m	8.03 f-l	44.80 b-d	36.32 d-k	1.83 d-i
23.	KS-118	51.67	60.67	131.33 a-c	23.33	22.16	25.32 a-d	10.41 b-g	8.33 b-j	45.15 b-d	25.39 h-k	1.30 e-i
24.	BS-131	52.83	61.33	130.67 a-c	22.59	21.59	23.15 a-d	10.32 b-h	8.54 a-i	47.16 b-d	22.79 jk	1.14 f-i
25.	BS-147	52.00	60.67	130.33 a-c	22.83	22.28	24.52 a-d	11.00 ab	8.54 a-i	45.42 b-d	26.38 h-k	1.33 e-i
26.	BS-146	52.83	61.50	129.33 c	24.06	21.45	25.39 a-d	9.77 b-l	8.84 a-f	35.02 d	28.47 h-k	1.11 f-i
27.	MU-140	53.00	62.17	129.33 c	21.91	19.58	33.36 a-c	8.03 o	8.34 b-j	43.43 b-d	33.30 d-k	1.52 e-i
28.	BS-130	52.33	60.83	129.67 c	22.31	20.81	24.64 a-d	8.86 i-o	8.34 b-j	46.68 b-d	51.86 a-d	2.67 b-e
29.	KS-119	52.67	61.67	131.67 bc	21.97	21.65	21.55 a-d	10.08 b-j	8.37 b-i	41.44 b-d	21.53 jk	1.08 f-i
30.	MU-139	52.33	61.33	130.67 a-c	23.50	22.92	20.70 b-d	9.43 e-n	8.06 f-l	52.37 b-d	20.62 k	1.19 f-i
31.	MU-137	52.00	61.00	131.33 a-c	24.71	21.74	20.63 b-d	8.59 l-o	7.47 j-l	65.95 ab	20.60 k	1.60 d-i
32.	BS-148	52.17	60.83	131.00 a-c	23.82	22.51	21.09 a-d	9.69 c-m	8.39 b-i	43.17 b-d	24.02 i-k	1.14 f-i
33.	MU-138	51.67	60.83	131.33 a-c	23.02	24.16	22.45 a-d	9.77 b-l	7.80 h-l	46.87 b-d	22.49 jk	1.14 f-i

34.	BS-105	52.00	60.83	130.67 a-c	23.55	21.69	29.11 a-d	8.56 l-o	8.15 d-l	37.95 cd	33.53 d-k	1.33 e-i
35.	BS-133	51.50	60.00	130.33 a-c	22.36	21.64	27.36 a-d	8.62 l-o	8.33 b-j	40.45 cd	50.33 a-e	2.34 b-h
36.	BS-101	51.67	60.50	129.33 c	24.20	23.67	21.90 a-d	10.50 b-f	8.32 b-j	41.84 b-d	23.79 i-k	1.02 g-i
37.	BS-104	51.83	60.67	130.33 a-c	22.41	22.10	26.45 a-d	8.41 m-o	7.42 kl	49.35 b-d	28.97 h-k	1.54 e-i
38.	BS-106	50.67	59.50	130.00 a-c	24.70	22.07	29.61 a-d	9.34 f-n	7.79 h-l	35.71 d	34.28 d-k	1.25 f-i
39.	BS-141	52.33	61.00	131.00 a-c	22.44	20.32	17.88 d	8.85 i-o	8.15 e-l	40.35 cd	35.75 d-k	1.54 e-i
40.	BS-115	52.67	61.17	130.67 a-c	23.42	20.91	24.23 a-d	9.95 b-k	8.02 f-l	37.11 cd	24.15 i-k	1.00 g-i
41.	KS-117	51.17	60.17	131.33 a-c	21.67	21.52	26.98 a-d	10.30 b-h	8.26 b-l	37.44 cd	27.01 h-k	1.13 f-i
42.	BS-143	52.33	61.00	130.67 a-c	23.15	20.29	20.02 b-d	10.03 b-j	8.24 c-l	40.92 cd	19.95 k	0.92 hi
43.	BS-103	52.17	61.00	130.33 a-c	23.08	20.35	26.23 a-d	8.83 j-o	7.40 l	39.61 cd	28.03 h-k	1.18 f-i
44.	BS-102	51.83	60.67	129.67 bc	23.68	20.90	20.75 b-d	9.97 b-k	8.17 d-l	42.82 b-d	23.48 jk	1.01 g-i
45.	BS-132	51.83	60.33	130.00 a-c	23.56	22.53	18.47 d	8.87 i-o	8.44 b-i	40.29 cd	18.51 k	0.84 i
P Value		0.715	0.588	<0.0001	0.807	0.092	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Standard Error		0.627	0.627	0.402	1.193	1.232	2.400	0.230	2.400	4.365	3.288	0.250
Season 1		51.53 b	60.99 b	129.64 b	26.64 a	22.39	33.17 a	10.44 a	8.97 a	63.14 a	41.80 a	2.68 a
Season 2		53.12 a	61.38 a	131.64 a	20.67 b	21.71	17.38 b	8.92 b	7.71 b	28.84 b	22.89 b	0.65 b
P Value		<0.0001	0.037	<0.0001	<0.0001	0.066	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Standard Error		0.141	0.132	0.085	0.251	0.260	0.506	0.048	0.032	0.920	0.693	0.053

Key: Means followed by the same letter are not significantly different based on Tukey's Honest Significant Difference (HSD) at α = 0.05. HSW= Weight of 100 seeds, DTFF = Days to first flowering, D50%F = Days to 50% flowering, DTM = Days to maturity

4.1.4.4 Overall variation of quantitative traits in all sites

Combined data from the three study sites showed that there were highly significant ($P<0.0001$) differences in days to maturity among the landraces but they did not differ significantly ($P>0.05$) in days to 50% flowering and days to first flowering (Table 4.6). Days to first flowering ranged from 51 to 53 days while days to 50% flowering ranged from 59 to 61 days. Days to maturity varied between 130 days and 132 days in BS-147 and BS-132 respectively (Table 4.6). All the phenological parameters varied significantly ($P<0.0001$) between seasons, with season 1 having shorter days to first flowering and days to maturity (Table 4.6). There were no significant ($P>0.05$) differences in plant height and number of tillers (Table 4.5). Plant height varied from 23.07 cm to 26.45 cm, while the number of tillers varied from 20 to 24. The two growth variables portrayed high significant ($P<0.0001$) seasonal differences with season 1 having higher growth values (Table 4.6).

The study also showed that all the yield traits assessed showed highly significant variations ($P<0.0001$) (Table 4.6). The study further revealed that there were highly significant differences in all the yield traits evaluated (Table 4.6). Number of pods varied between 21 and 36 in KS-120 and BS-101 respectively. LU-124 recorded the longest seed length of 11.74 mm while BS-130 recorded the shortest seed length of 8.26 mm. BS-144 recorded the longest seed width of 9.30 mm while MU-137 recorded the shortest seed width of 7.45 mm. BG-110 recorded the highest weight of 100 seeds of 56.63 g while BS-132 recorded the lowest value with 32.58 g. BS-107 recorded the highest number of seeds (61) while MU-137 recorded the lowest (21). The landrace BS-107 recorded the highest average yield of 2.74 t ha^{-1} while the landrace BS-132 had the lowest average yield of 0.80 t ha^{-1}. There were highly significant ($P<0.0001$) seasonal variations for all the yield variables with lower yield values being recorded in the second cropping season (Table 4.6).

Table 4.6: Variation in growth and yield traits of Bambara groundnut landraces across the three sites

No.	Landrace	DTFF	DT50%F	DTM	Plant height (cm)	No. of tillers	Seed length (mm)	Seed width (mm)	No. of pods	Wgt of 100 seeds (g)	No. of seeds	Yield (t/ha)
1.	BG-110	52.39	61.61	131.78 a-e	26.45	24.53 ab	11.19ab	8.56 d-l	26.47 b-h	56.63 a	26.38 i-m	1.69 d-l
2.	BG-112	52.61	61.89	131.33 c-e	25.40	21.63 a-c	11.09 a-c	8.97 a-e	29.96 a-f	53.30 a-c	30.02 h-m	1.74 d-k
3.	BG-111	52.72	61.78	131.78 a-e	24.90	20.81 bc	10.95 a-e	8.60 c-k	28.42 a-h	47.66 a-g	28.30 h-m	1.47 f-n
4.	LU-124	52.78	61.61	131.89 a-e	23.83	24.96 a	11.74 a	9.03 a-d	24.17 b-h	50.84 a-e	24.13 j-m	1.32 g-n
5.	BS-113	53.22	61.56	131.00 de	24.83	24.04 a-c	11.28 ab	8.81 a-g	26.28 b-h	47.52 a-g	26.28 i-m	1.31g-n
6.	KS-108	52.00	61.11	131.78 a-e	24.22	24.03 a-c	10.08 a-f	8.74 b-i	32.15 ab	42.67 b-h	32.10 g-l	1.40 g-n
7.	BG-109	51.78	60.94	131.78 a-e	25.78	22.78 a-c	10.14 a-f	8.72 b-j	26.46 b-h	55.62 ab	26.43 i-m	1.60 e-m
8.	KS-116	52.39	61.28	132.67 ab	23.95	23.86 a-c	9.48 a-f	8.31 h-p	23.50 d-h	43.55 a-h	47.39 b-e	2.17 a-f
9.	BS-107	52.94	61.50	131.33 c-e	24.14	21.45 a-c	9.62 a-f	8.40 f-o	30.70 a-e	40.91 c-h	61.41 a	2.74 a
10.	LU-121	52.33	61.22	131.78 a-e	23.44	22.15 a-c	10.51 a-f	7.97 n-s	25.35 b-h	50.03 a-f	50.68 a-c	2.69 ab
11.	BG-125	52.22	61.00	132.78 a	24.10	23.47 a-c	10.45 a-f	8.09 l-r	27.55 b-h	44.10 a-h	27.73 i-m	1.26 g-n
12.	BS-114	52.28	60.83	131.22 c-e	24.10	23.81 a-c	9.90 a-f	9.08 a-c	22.94 e-h	47.03 a-g	45.85 b-e	2.32 a-e
13.	BS-144	52.39	60.44	131.56 a-e	24.08	22.09 a-c	8.57 c-f	9.30 a	26.66 b-h	42.42 b-h	53.30 ab	2.44 a-d
14.	MU-138	52.06	61.06	132.33 a-c	25.15	24.02 a-c	9.82 a-f	8.01 n-s	27.18 b-h	41.01 c-h	27.21 i-m	1.17 h-n
15.	MU-136	51.89	60.72	131.33 c-e	24.67	22.90 a-c	9.06 b-f	9.11 ab	28.21 a-h	41.88 b-h	28.29 i-m	1.35 g-n
16.	BS-134	52.28	60.56	131.89 a-e	23.80	20.82 bc	9.08 b-f	8.99 a-e	23.40 d-h	47.36 a-g	46.62 b-e	2.69 ab
17.	LU-122	52.06	60.83	132.00 a-e	24.02	22.32 a-c	8.46 d-f	7.79 q-t	23.23 e-h	52.59 a-d	46.41 b-e	2.51 a-c
18.	KS-120	52.39	61.06	131.56 a-e	24.39	21.62 a-c	10.49 a-f	8.33 g-p	21.01 h	40.46 c-h	41.99 c-g	1.78 c-j
19.	BS-129	52.22	60.56	131.11 c-e	24.91	24.04 a-c	9.40 a-f	8.30 h-p	23.62 d-h	38.73 d-h	39.03 d-h	1.84 c-i
20.	BS-101	51.67	60.22	130.89 e	23.49	24.60 ab	10.56 a-f	8.44 f-n	36.08 a	40.01 c-h	36.71 e-i	1.48 f-n
21.	LU-123	52.44	61.11	131.44 b-e	24.47	24.40 ab	10.31 a-f	8.18 k-q	22.34 f-h	43.70 a-h	22.36 k-m	1.02 j-n
22.	MU-135	51.33	60.22	132.00 a-e	24.29	22.33 a-c	10.62 a-f	8.77 b-h	26.15 b-h	38.53 e-h	27.09 i-m	1.12 i-n
23.	BS-145	52.44	60.56	131.61 a-e	24.31	21.29 a-c	8.97 b-f	7.78 q-t	26.56 b-h	43.81 a-h	27.16 i-m	1.31 g-n
24.	KS-118	51.61	60.44	132.00 a-e	24.21	22.78 a-c	11.15 a-c	8.37 f-o	23.11 e-h	42.03 b-h	23.10 j-m	1.04 j-n
25.	BS-133	52.44	60.61	130.89 e	23.35	23.10 a-c	8.75 b-f	8.36 f-o	25.03 b-h	35.93 gh	48.58 b-d	1.91 c-h
26.	BS-141	52.50	60.67	131.56 a-e	24.61	21.35 a-c	9.04 b-f	8.13 k-r	21.58 gh	34.92 gh	43.18 b-f	1.52 f-n
27.	BS-103	51.67	60.11	131.44 b-e	24.49	22.25 a-c	9.25 a-f	7.65 r-t	30.24 a-f	40.09 c-h	30.84 h-m	1.30 g-n
28.	MU-139	51.83	60.67	132.11 a-e	24.46	24.20 a-c	9.78 a-f	8.18 k-q	21.41 gh	41.35 c-h	21.37 lm	0.94 l-n
29.	BS-106	51.56	60.00	131.00 de	25.00	23.18 a-c	9.82 a-f	8.03 m-r	31.898 a-c	35.63 gh	33.46 f-j	1.24 g-n
30.	BS-104	51.78	60.28	131.33 c-e	24.00	21.62 a-c	9.04 b-f	7.53 st	29.38 a-g	46.45 a-h	30.22 h-m	1.43 f-n
31.	BS-146	52.17	60.28	131.11 c-e	24.60	20.51 c	10.10 a-f	8.83 a-f	25.46 b-h	35.48 gh	26.50 i-m	1.04 j-n
32.	MU-140	52.06	61.00	131.33 c-e	23.98	21.06 bc	8.40 ef	8.45 f-n	26.70 b-h	39.96 c-h	26.69 i-m	1.10 i-n

33.	BS-105	51.72	60.11	131.44 b-e	24.17	23.16 a-c	8.39 ef	7.93 o-t	31.37 a-d	36.85 f-h	32.84 f-k	1.29 g-n
34.	KS-119	51.67	60.56	132.22 a-d	23.38	22.84 a-c	11.03 a-d	8.39 f-o	22.43 f-h	39.50 c-h	22.42 k-m	0.98 k-n
35.	BS-143	52.06	60.17	131.56 a-e	24.09	22.00 a-c	10.09 a-f	8.52 e-m	23.12 e-h	40.19 c-h	23.08 j-m	1.01 k-n
36.	MU-137	51.94	60.72	132.11 a-e	24.77	21.88 a-c	8.95 b-f	7.45 t	21.21 h	43.04 a-h	21.18 m	1.04 j-n
37.	BS-147	51.50	59.67	130.89 e	23.53	23.55 a-c	10.59 a-f	8.52 e-m	25.92 b-h	39.64 c-h	26.48 i-m	1.15 i-n
38.	BS-115	52.22	60.56	131.28 c-e	24.18	21.62 a-c	10.53 a-f	7.86 p-t	24.53 b-h	38.71 d-h	24.46 j-m	1.02 j-n
39.	BS-148	51.67	59.83	132.11 a-e	23.66	21.14 a-c	9.92 a-f	8.38 f-o	24.05 c-h	41.73 b-h	25.02 j-m	1.16 h-n
40.	KS-117	51.17	60.11	131.89 a-e	23.07	22.31 a-c	11.25 ab	8.33 g-p	25.26 b-h	37.11 e-h	25.27 j-m	1.00 k-n
41.	BS-131	52.00	60.17	131.56 a-e	24.07	21.74 a-c	10.22 a-f	8.45 f-n	22.70 e-h	39.52 c-h	22.58 k-m	0.98 k-n
42.	BS-102	52.22	60.72	131.11 c-e	23.17	22.09 a-c	10.06 a-f	8.26 i-q	23.93 c-h	37.42 e-h	24.87 j-m	0.94 l-n
43.	BS-130	51.56	59.78	131.56 a-e	23.81	21.17 a-c	8.26 f	8.24 j-q	22.83 e-h	39.52 c-h	46.52 b-e	1.97 b-g
44.	BS-142	51.89	60.06	131.11 c-e	23.95	21.88 a-c	10.53 a-f	8.42 f-n	22.36 f-h	36.41 f-h	22.72 j-m	0.85 mn
45.	BS-132	51.61	59.83	131.05 c-e	24.59	23.34 a-c	8.87 b-f	8.51 e-m	21.89 gh	32.58 h	21.91 lm	0.80 n
P Value		0.077	0.103	<0.0001	0.288	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Standard Error		0.375	0.434	0.230	0.629	0.693	0.467	0.088	1.428	2.486	1.914	0.136
Season 1		51.84 b	61.05 a	130.59 b	26.05 a	23.01 a	26.05 a	8.88 a	32.02 a	54.52 a	40.12 a	2.20 a
Season 2		52.32 a	60.29 b	132.59 a	22.48 b	22.18 b	22.48 b	7.88 b	19.30 b	30.12 b	24.15 b	0.74 b
P Value		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Standard Error		0.079	0.091	0.230	0.133	0.146	0.133	0.018	0.301	0.524	0.404	0.029
Kangaru		52.33 a	60.96 a	132.43 a	21.95 c	22.46 b	9.56 b	8.36 ab	23.22 c	41.61 b	28.78 c	1.27 c
Ishiara		51.60 b	59.86 b	131.70 b	27.19 a	23.28 a	10.48 a	8.44 a	28.49 a	39.36 c	35.28 a	1.47 b
Kiamuringa		52.32 a	61.18 a	130.64 c	23.66 b	22.05 b	9.68 b	8.34 b	25.28 b	45.99 a	32.35 b	1.67 a
P Value		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.007	<0.0001	<0.0001	<0.0001	<0.0001
Standard Error		0.097	0.112	0.059	0.162	0.179	0.121	0.023	0.369	0.642	0.494	0.035

Key: Means followed by the same letter are not significantly different based on Tukey's Honest Significant Difference (HSD) at α = 0.05. DTFF = Days to first flowering, D50%F = Days to 50% flowering, DTM = Days to maturity

4.1.5 Interactions between genotypes and locations and seasons

The interactions between locations, genotypes and seasons are summarized in Table 4.7. The interactions of genotype and location (G x L) on number of pods, weight of 100 seeds, days to maturity seed width, number of seeds and yield were highly significant (P<0.0001). For genotype and location (G x S) interaction, there were no significant (P>0.05) interactions for plant height, days to 50% flowering, number of tillers, days to first flowering and seed length. Further analysis of the results revealed significant (P<0.05) to highly significant (P<0.0001) interactions between genotype and season (G x S) for plant height, weight of 100 seeds, seed width, number of seeds, and yield but no significant (P>0.05) interactions for days to 50% flowering, days to maturity, number of tillers, number of pods, days to first flowering and seed length. Additionally, the weight of 100 seeds and the yields were significantly affected by the genotype, location, and season (G x L x S) interaction, although other variables did not exhibit a significant G x L x S interaction (Table 4.7).

Table 4.7: P values of interactions among genotypes, locations and seasons for agronomic traits in combined analysis of variance

	Traits										
Interaction	**DTFF**	**D50%F**	**DTM**	**Plant height**	**Number of tillers**	**Number of pods**	**Seed length**	**Seed width**	**Weight of 100 seeds**	**Number of seeds**	**Yield**
G x L	0.098^{NS}	0.867^{NS}	$<0.0001^{***}$	0.829^{NS}	0.970^{NS}	$<0.0001^{***}$	0.424^{NS}	$<0.0001^{***}$	$<0.0001^{***}$	$<0.0001^{***}$	$<0.0001^{***}$
G x S	1.000^{NS}	0.559^{NS}	1.000^{NS}	0.050^{*}	0.250^{NS}	0.999^{NS}	0.430^{NS}	$<0.0001^{***}$	$<0.0001^{***}$	$<0.0001^{***}$	$<0.0001^{***}$
G x L x S	0.285^{NS}	0.884^{NS}	1.000^{NS}	0.649^{NS}	1.000^{NS}	1.000^{NS}	0.830^{NS}	$<0.0001^{***}$	0.022^{*}	0.999^{NS}	$<0.0001^{***}$

Key: NS = Not Significant; *Significant at 5%; ***Significant at 0.1%; L = Location, G = Genotype, S = Season. DTM = Days to maturity, D50%F = Days to 50% flowering and DTFF = Days to first flowering

4.1.6 Discriminant analysis of variations in the sites

The sites variation was further assessed through Discriminant Analysis (DA) as presented in Figure 4.4. The first factor (F1) and second factor (F2) explained variability of 76.81% and 23.19% respectively. The analysis isolated Ishiara from the other two sites. There was an overlap of the landraces in Kangaru and Kiamuringa.

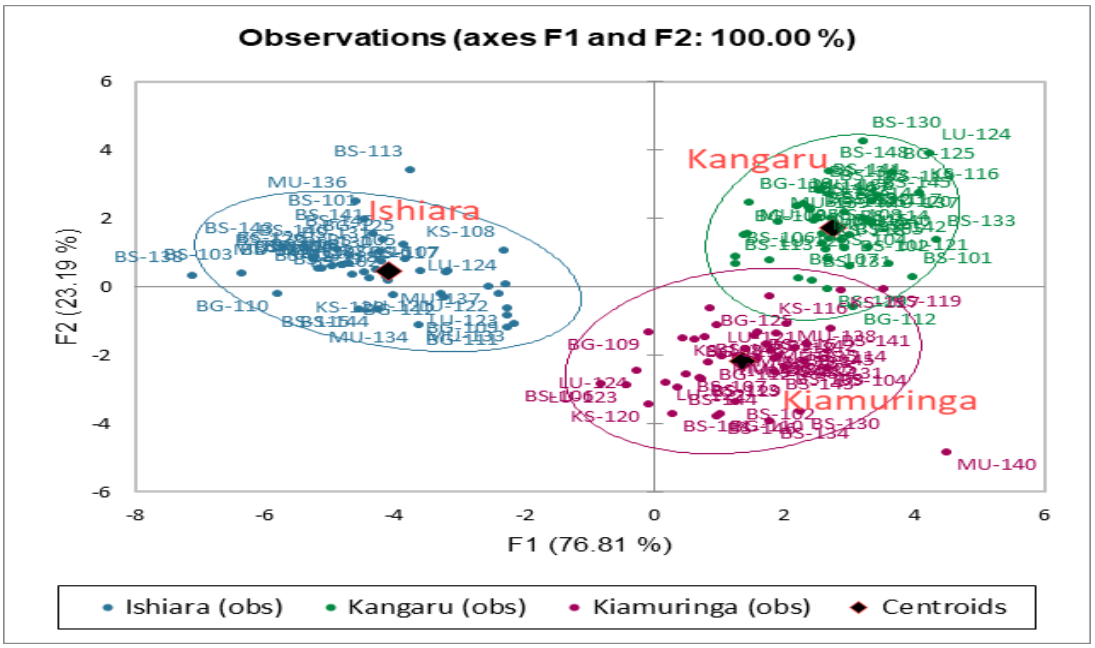

Figure 4.4: Pictorial illustration of site variations using discriminant analysis

4.1.7 Pearson correlation between the phenological, growth and yield traits

Table 4.8 shows the findings of the Pearson correlation analysis between the agro-morphological characters are shown. Days to first flowering had a positive and significant correlation with days to 50% flowering ($r = 0.778$, $P<0.0001$), weight of 100 seeds ($r = 0.400$, $P<0.007$), number of seeds per plant ($r = 0.329$, $P<0.027$) and overall yield ($r = 0.415$, $P<0.005$). Similarly, days to 50% flowering was positively and significantly associated with plant height ($r = 0.411$, $P<0.005$), weight of 100 seeds ($r = 0.661$, $P<0.0001$), seed length ($r = 0.341$, $P<0.022$) and overall yield ($r = 0.344$ $P<0.021$). Plant height and weight of 100 seeds had positive and significant correlation ($r = 0.384$, $P<0.009$). Days to maturity correlated positively and significantly with weight of 100 seeds ($r = 0.303$, $P<0.043$). Yield had positive and significant correlation with weight of 100 seeds ($r = 0.427$, $P<0.003$) and number of seeds ($r = 0.917$, $P<0.0001$). Conversely, seed length showed a negative and significant correlation with number of seeds ($r = -0.415$, $P<0.005$).

Table 4.8: Pearson correlation between the growth and yield traits of Bambara groundnuts

Variables	DTFF									
D50%F	**0.778*****	**D50%F**								
DTM	-0.072	0.242	**DTM**							
Plant height	0.250	**0.411****	-0.017	**PH**						
No. of tillers	0.013	0.194	0.048	0.142	**NoT**					
Seed length	0.128	**0.341***	0.095	0.093	0.289	**SL**				
Seed width	0.230	0.218	-0.166	0.075	0.111	0.292	**SW**			
No. of pods	-0.037	0.098	-0.255	0.108	0.129	0.024	0.022	**NoP**		
W100S	**0.400****	**0.661*****	**0.303***	**0.384****	0.152	0.277	0.176	0.073	**W100S**	
No. of seeds	**0.329***	0.158	-0.069	-0.229	-0.142	**-0.415****	0.086	0.114	0.073	**NoS**
Yield t/ha	**0.415****	**0.344***	0.055	-0.082	-0.108	-0.287	0.172	0.078	**0.427****	**0.917*****

Key: Values in bold are not equal to zero (0) at alpha = 0.05. *Significant at 5%, **Significant at 1%, ***Significant at 0.1%. DTFF = Days to first flowering, D50%F = Days to 50% flowering, DTM = Days to maturity, PH = Plant height, NoT = Number of tillers, SL = Seed length, SW = Seed width, NoP = Number of pods, W100S = Weight of 100 seeds, NoS = Number of seeds

4.2 Nutritional and phytochemical composition of Bambara groundnut

Seventeen (17) most commonly consumed landraces were selected and used for nutritional and phytochemical characterization.

4.2.1 Proximate and nutritional composition of the Bambara groundnut

The proximate and nutritional composition of the Bambara groundnut landraces used in this study is shown in Table 4.9. There was significant difference ($P<0.05$) in all the nutritional traits evaluated in the combined data for both seasons. The moisture content ranged from 3.47% in landrace LU-123 to 6.24% in landrace BG-125. The total ash content ranged from 3.17% in BS-141 to 4.70% in BS-114. The landrace BS-114 also had the highest mean value of crude protein (26.00%) while KS-116 had the lowest mean value of crude protein (21.18%). The fat content ranged from 4.56% in BS-114 to 6.93% in KS-116. Therefore, BS-114 had the highest protein and total ash content but the lowest fat content. The composition of minerals in Bambara groundnut followed the order Potassium (K) > Sodium (Na) > Iron (Fe) > Zinc (Zn) with the most abundant element (Table 4.9). The landrace BG-125 had the highest iron content of 5.13mg/100g while BG-112 had the lowest iron content of 4.07 mg/ 100g. Zinc content ranged between 0.06 mg/100g and 0.42 mg/100g in landraces BS-104 and BG-125, respectively. Potassium ranged from 819.34 mg/100 in landrace BS-103 to 1,133.80 mg/100g in landrace BS-145. The highest sodium content was obtained in landrace LU-123 with 129.66 mg/100g while landrace MU-137 had the lowest value of 25.14 mg/100g (Table 4.9). Landrace x season interactions were not significant ($P>0.05$) for all the tested biochemical components.

Table 4.9: Nutritional composition of the selected Bambara groundnut landraces

S.no	Landrace	Moisture (%)	Total ash (%)	Fats (%)	Protein (%)	Fe (mg/100 g)	Zn (mg/100 g)	K (mg/100 g)	Na (mg/100 g)
1.	LU-123	3.47 i	4.20 b-e	6.55 b	24.54 bc	4.74 b-d	0.26 a-c	1031.11 b-d	129.66 a
2.	BS-114	4.89 d-f	4.69 a	4.56 h	26.00 a	4.62 c-e	0.17 a-c	1063.19 a-c	118.31 c
3.	MU-137	5.85 b	4.23 b-d	5.81 de	22.04 ij	4.917 a-c	0.11 c	934.84 ef	25.14 o
4.	BG-125	6.24 a	4.07 d-f	7.02 a	21.81 j	5.125 a	0.42 a	994.54 c-e	27.29 n
5.	BS-148	4.62 fg	4.27 b-d	4.97 g	24.90 b	4.86 a-d	0.09 c	1082.86 ab	44.91 k
6.	BS-104	5.82 b	3.94 ef	6.24 bc	22.49 hi	4.96 ab	0.06 c	820.39 g	27.47 n
7.	KS-118	3.79 hi	4.03 d-f	6.22 bc	22.44 h-j	4.62 c-e	0.23 a-c	1044.43 b-d	104.52 d
8.	BS-102	5.65 bc	4.46 ab	5.49 ef	23.25 fg	4.84 a-d	0.23 a-c	964.15 d-f	64.97 g
9.	LU-124	3.49 i	4.23 b-d	6.14 cd	24.19 cd	4.84 a-d	0.22 a-c	997.36 c-e	52.05 h
10.	BS-103	5.07 d	3.59 g	5.98 cd	22.92 gh	4.84 a-d	0.37 ab	819.34 g	49.48 i
11.	BS-145	4.68 e-g	4.14 c-e	5.40 f	24.36 bc	4.68 b-e	0.13 bc	1133.80 a	66.52 f
12.	BS-141	4.99 de	3.17 h	6.05 cd	24.40 bc	4.59 de	0.07 c	983.07 c-e	36.62 l
13.	KS-116	3.68 i	3.83 fg	6.93 a	21.18 k	4.82 a-d	0.09 c	974.68 de	29.36 m
14.	BS-142	4.50 g	4.05 d-f	5.61 ef	23.92 c-e	4.37 ef	0.24 a-c	982.71 c-e	80.79 e
15.	BG-112	4.03 h	4.40 bc	5.81 de	23.17 fg	4.07 f	0.08 c	1108.54 ab	81.08 e
16.	KS-108	5.44 c	4.10 d-f	5.62 ef	23.41 e-g	4.10 f	0.27 a-c	882.49 fg	122.25 b
17.	BG-109	4.71 e-g	4.01 d-f	5.59 ef	23.660 d-f	4.11 f	0.19 a-c	991.51 c-e	46.83 j
P value		$<0.0001^{***}$	$<0.0001^{***}$	$<0.0001^{***}$	$<0.0001^{***}$	$<0.0001^{***}$	$< 0.0001^{***}$	$<0.0001^{***}$	$<0.0001^{***}$
Standard Error		0.065	0.056	0.068	0.124	0.063	0.051	16.261	0.209
Season 1		4.79	4.09	5.89	23.49	4.68	0.19	988.81	65.20
Season 2		4.73	4.08	5.88	23.41	4.63	0.19	988.73	65.07
P Value		0.093^{NS}	0.679^{NS}	0.806^{NS}	0.165^{NS}	0.147^{NS}	0.843^{NS}	0.992^{NS}	0.193^{NS}
Standard Error		0.022	0.019	0.023	0.042	0.022	0.012	5.578	0.072
Landrace x Season		0.906	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Key: Means with the same letters within the column are not significantly different at $\alpha = 0.05$; *Significant at 5%, **Significant at 1%, ***Significant at 0.1%, NS – Not Significant

4.2.2 Phytochemical composition of the Bambara groundnut landraces

There were significant (P<0.05) differences between the landraces for their anti-nutrient components (Table 4.10). The composition of tannins ranged from 0.011 mg g^{-1} in landrace KS-108 to 0.037 mg g^{-1} in landrace BS-114. Saponins composition ranged between 0.815 mg/100g in landrace KS-108 and 1.057 mg/100g in landrace MU-137. The alkaloids content ranged from 0.011 mg/100g in landrace BG-109 to 0.116 mg/100g in landrace BS-103. Among the test landraces, BS-104 had the highest mean composition of flavonoids (8.450 mg/100g) while KS-108 had the lowest mean value (4.067 mg/100g). There were significant differences (P<0.05) between seasons for tannins, flavonoids and saponins concentrations but no significant difference (P>0.05) between the two seasons for alkaloid content in the tested landraces. Landrace x season interactions were not significant (P>0.05) for all the tested biochemical components.

Table 4.10: Phytochemical levels in the assessed Bambara groundnut landraces

S.No	landraces	Alkaloids (mg/100g)	Tannins (mg/g)	Saponins (mg/100g)	Flavonoids (mg/100g)
1.	LU-123	0.034 ab	0.033 a	0.907 de	6.553 g
2.	BS-114	0.036 ab	0.037 a	0.945 cd	6.220 h
3.	MU-137	0.039 ab	0.034 a	1.057 a	8.170 b
4.	BG-125	0.023 b	0.029 ab	0.875 ef	8.085 b
5.	BS-148	0.031 ab	0.028 ab	0.980 bc	7.480 d
6.	BS-104	0.036 ab	0.029 ab	1.003 b	8.450 a
7.	KS-118	0.032 ab	0.033 a	0.942 cd	6.175 h
8.	BS-102	0.024 b	0.029 ab	0.872 efg	6.822 f
9.	LU-124	0.030 ab	0.018 cd	0.843 fgh	8.185 b
10.	BS-103	0.116 a	0.023 bc	0.903 de	7.877 c
11.	BS-145	0.019 b	0.031 ab	0.870 efg	6.967 f
12.	BS-141	0.039 ab	0.029 ab	0.868 efg	6.837 f
13.	KS-116	0.023 b	0.034 a	1.002 b	7.277 e
14.	BS-142	0.021 b	0.032 ab	0.875 ef	5.440 i
15.	BG-112	0.027 b	0.018 cd	0.828 fgh	4.490 j
16.	KS-108	0.019 b	0.011 d	0.815 h	4.067 l
17.	BG-109	0.011 b	0.032 ab	0.820 gh	4.317 k
P value		0.047^{*}	$< 0.0001^{***}$	$< 0.0001^{***}$	$< 0.0001^{***}$
Standard Error		0.017	0.002	0.010	0.031
Season 1		0.039	0.030 a	0.920 a	6.695 a
Season 2		0.027	0.027 b	0.893 b	6.647 b
P value		0.171^{NS}	0.003^{**}	$< 0.0001^{***}$	0.002^{*}
Standard Error		0.006	0.001	0.003	0.011
Landrace x Season		0.480^{NS}	1.000^{NS}	0.992^{NS}	1.000^{NS}

Key: Means with the same letters within the column are not significantly different at α = 0.05; *Significant at 5%, **Significant at 1%, ***Significant at 0.1%, NS – Not Significant

4.2.3 Correlation of the nutritional and phytochemical components

Pearson correlation of the nutritional and phytochemical components of Bambara groundnut landraces is presented in Table 4.11. The saponins were found to be positively correlated to tannins and flavonoids. There was significant negative correlation between the alkaloids and potassium content while the flavonoid content was positively correlated to iron content but negatively correlated to the sodium content (Table 4.11). The protein content was negatively correlated to the fat content but positively correlated to the sodium content which was negatively correlated to the iron content.

Table 4.11: Pearson correlation between the nutritional and phytochemical components of Bambara groundnut landraces

Variables	Moisture										
Total ash	-0.042	**Total ash**									
Alkaloids	0.113	-0.358	**Alkaloids**								
Tannins	0.050	0.165	-0.188	**Tannins**							
Saponins	0.140	0.044	0.177	**0.490***	**Saponins**						
Flavonoids	0.221	-0.169	0.368	0.283	**0.590***	**Flavonoids**					
Fats	-0.113	-0.461	-0.006	-0.162	0.068	0.324	**Fats**				
Protein	-0.229	0.276	-0.027	0.206	-0.285	-0.239	**-0.721*****	**Protein**			
Iron	0.263	-0.060	0.263	0.382	**0.595***	**0.956*****	0.345	-0.253	**Iron**		
Sodium	-0.376	0.418	-0.115	-0.128	-0.316	**-0.597***	-0.313	**0.489***	**-0.485***	**Sodium**	
Potassium	-0.473	0.429	**-0.489***	0.347	-0.169	-0.254	-0.287	0.438	-0.195	0.285	**Potassium**
Zinc	0.177	0.009	0.253	-0.250	-0.373	0.007	0.269	-0.130	0.141	0.231	-0.253

NB: Values in bold are not equal to zero (0) at alpha = 0.05 significance level. *Significant at 5%, **Significant at 1%, ***Significant at 0.1%

4.2.4 Principal component analysis

To display the association between the Bambara groundnut landraces and the nutritional and phytochemical traits evaluated, the Principal Component Analysis (PCA) was utilized (Figure 4.4). The PCA was useful in determining the most important components that were used in discriminating the different landraces. The first two principal components (PC1 and PC2) explained 52.11% of the total variation with PC1 explaining variability of 32.19%, PC2 with 19.92%. The landraces that were plotted closer to specific components indicated that those components had a relatively higher contribution in discriminating those landraces from the others. The tannins, saponins, flavonoids and iron were very important in separating the landraces MU-137, BS-104 and KS-116. The content of moisture, fats, alkaloids and zinc had a higher contribution in discriminating the landraces BS-141, BG-125 and BS-103. Total ash, potassium and protein contents were the most important components in separating the landraces BS-114, BS-145, BS-148 and BS-102. Sodium content was the most important component in discriminating the landraces LU-123, KS-108, BG-112, KS-118, BS-142, BG-109 and LU-124.

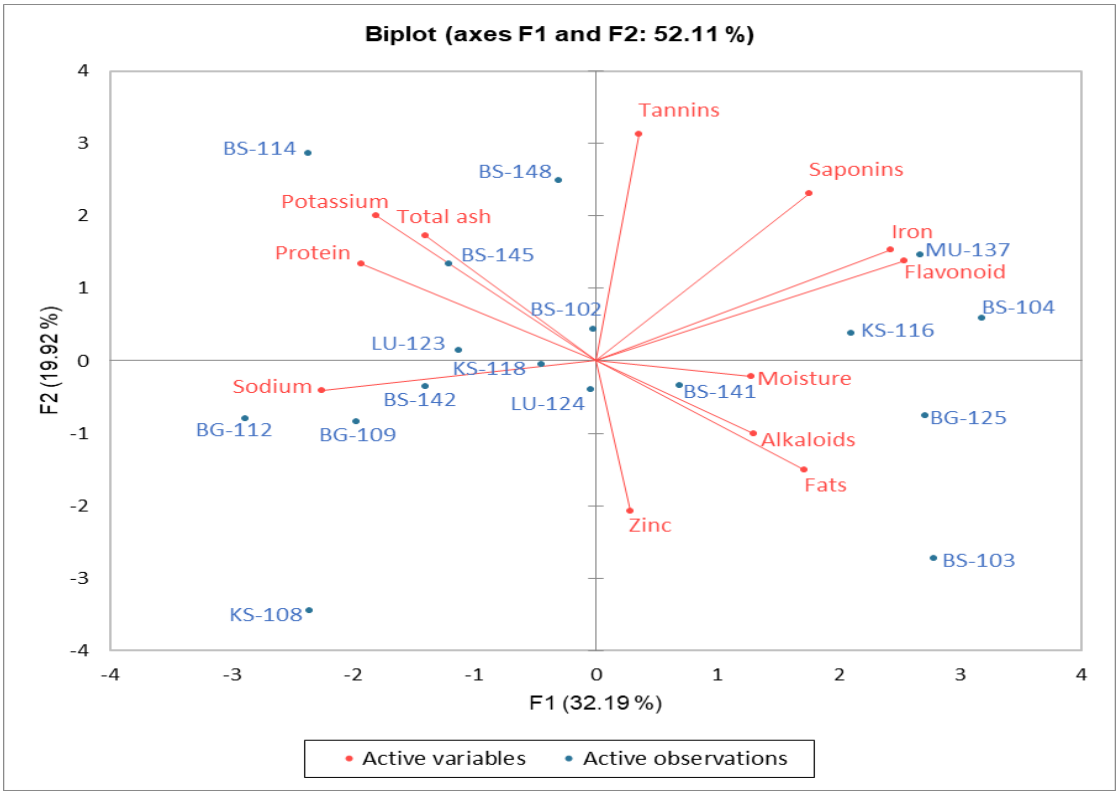

Figure 4.5: Principal nutritional and phytochemical components in the assessed landraces

4.2.5 Cluster analysis based on nutritional and phytochemical traits

Cluster analysis based on phytochemical and nutritional components was used to estimate the degree of similarity and diversity among the different Bambara groundnut landraces evaluated in this study. The 17 landraces were grouped into five (5) supported clusters (Figure 4.5) with a diversity of 94.02% between clusters and 5.98% within clusters. Cluster 1 was a singleton of landrace KS-108. Cluster 2 contained only two landraces, BS-103 and BS-104, both of which were collected from Busia County. These two landraces had medium levels of moisture, total ash, fat, protein, iron and potassium, but low levels of zinc and sodium. Cluster 3 was the largest comprising of eight landraces namely MU-137, BG-109, LU-124, BG-125, BS-141, KS-116, BS-102 and BS-142 which had no clear unique attributes. Cluster 4 consisted of landraces LU-123, BS-114 and KS-118 characterized with high levels of alkaloids and tannins. Cluster 5 consisted of landraces BS-148, BG-112 and BS-145 with high potassium levels and moderate to low sodium levels. The cluster analysis did not depict any significant influence of the origin of the landraces but was based mainly on the phytochemical and nutritional composition of selected Bambara groundnut landraces.

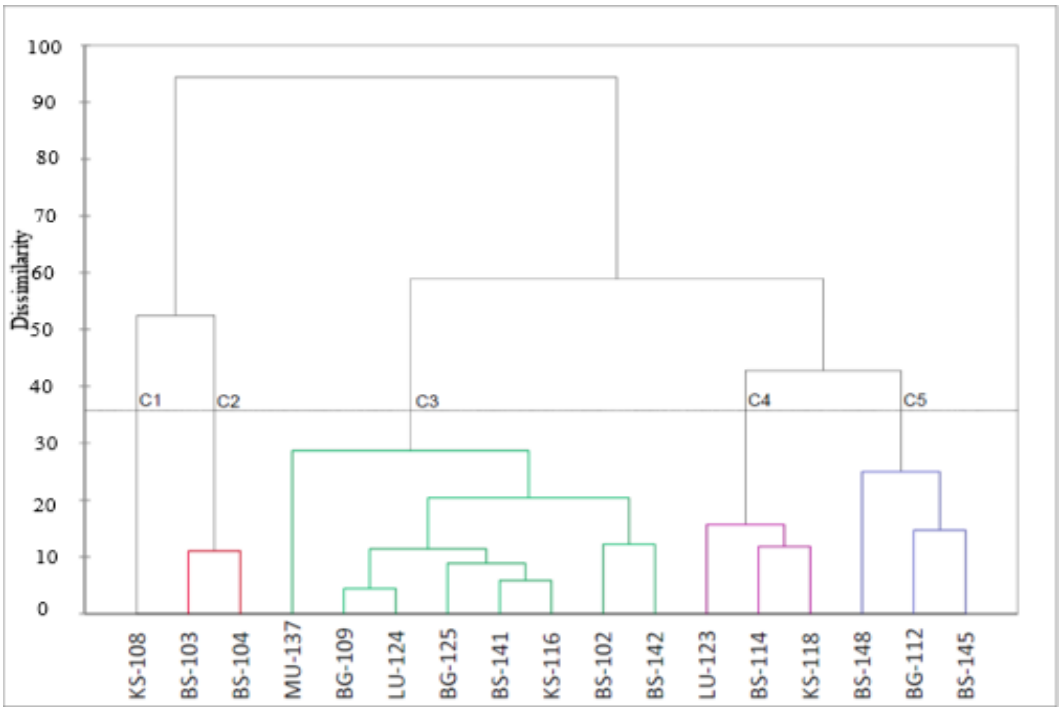

Figure 4.6: Dendrogram depicting the diversity of the assessed landraces based on nutritional and phytochemical composition

CHAPTER FIVE
DISCUSSION

5.1 Agro-morphological diversity

The observed highly significant differences in majority of morphological and agronomic characteristics among the landraces of Bambara groundnut assessed showed existence of variability that can be utilized in selection of superior varieties in plant breeding. The existence of considerable amount of variations in terms of morphological and agronomic characteristics among Bambara groundnut have been reported by other researchers (Bonny *et al*. 2019; Ntundu *et al*. 2006; Aliyu *et al*. 2016). Except for seed shape, the observed considerable diversity in qualitative features is consistent with observations of Khan *et al.* (2021) and Gbaguidi *et al.* (2018) whose findings had significant variations in all qualitative traits assessed.

The qualitative and quantitative agro-morphological variables were used to develop a cluster dendrogram. The landraces separated into five distinct clusters with diversity between clusters of 77.40% and 22.60% diversity within clusters. There was a significant level of genetic variation among the landraces, which further highlights the enormous selection potential that exists within Bambara groundnut landraces in Kenya. Previous studies by Unigwe e*t al.* (2016) in South Africa and Khaliqi *et al.* (2021) on Bambara groundnut sourced from Nigeria also reported high genetic diversity. High morphological diversity in Kenyan slender leaf and in horned melon grown in Kenya were outlined by Mwakha *et al*. (2020) and Owino *et al*. (2020) respectively. In contrast, Gichimu *et al*. (2009) found a low genetic diversity in watermelon accessions in Kenya. Bambara groundnut that clustered together indicated that they shared agro-morphological characteristics. Cluster analysis based on agro-morphological traits helps in selection of best parent lines for hybridization (Khan *et al.*, 2020). There was no relationship that was observed between areas of collection and genetic divergence of landraces as landraces from one collection point grouped in different clusters. Thus, there was no connection between geographic and genetic diversity (Tripathi *et al*., 2015). Similar results were found by Ntundu *et al.* (2006), who noted that Bambara groundnut landraces gathered from Tanzania's Western Lake Victoria and Central agricultural zones tended to group together. This association may have resulted from frequent farmer exchanges of germplasm (Ntundu *et al.*, 2006).

The relationship between the quantitative variables and tested Bambara groundnut landraces was presented using principal component analysis (PCA). Although variations in number of days to 50% flowering and in number of days to first flowering were not significant, PCA analysis indicated that the two characters had the highest impact on principal component 1 (PC1). The first two principal components (PC1 and PC2) accounted for 48.23% of the total variation which was slightly higher that 46% and 42% found by Ngomuo *et al.* (2017) and Akin-Idowu *et al*. (2016) for jute marrow and amaranth species, respectively. Seed width, days to 50% flowering, number of seeds and days to maturity were the principal components determining the variability of Bambara groundnut landraces. These agro-morphological traits can, therefore, be utilized in hybridization (Mwakha *et al*., 2020). Number of pods, days to first flowering, number of seeds and yield had higher impact in discriminating BS-107, BS-114, BS-129, BS-144, BS-134, KS-116, KS-120 LU-122 and LU-121. Number of days to 50% flowering, number of tillers, seed length, plant height, number of days to maturity, weight of 100 seeds and seed width had higher impact on discriminating the landraces BG-112, MU-136, BG-110, MU-138, KS-108, LU-123, BG-125, LU-124, BG-111, BS-113 and BG-109.

The studied Bambara groundnut landraces showed significant variation in all quantitative agro-morphological traits. Days to first flowering ranged between 51 to 53 days (Kangaru), 50-54 days (Ishiara) and (50-53 days) Kiamuringa. These were in contrast with 30-55 days reported by Brink & Belay (2006) in Bambara groundnut grown in Burkina Faso. In contrast to this study's results, which reported 60-63 days (Kangaru), 58-62 days (Ishiara) and 59-62 days (Kiamuringa) for days to 50% flowering, Brink & Belay (2006), Gedebo & Donkor, (2018) and Amadou *et al.* (2015) reported 32-42 days, 30-37 days and 33-40 days in Bambara groundnut grown in Burkina Faso, Ghana and Niger respectively. In an experiment conducted in South Africa by Mabhaudhi & Modi (2013), Bambara groundnuts took 64-66 days after planting for number of days to 50% flowering. The number of days to maturity reported in this study for Kangaru (130-133 days), Ishiara (130-132 days) and Kiamuringa (129-132 days) differed from those reported by Khan *et al.* (2021b) for Bambara groundnuts grown in Malaysia which ranged from 122 to 141 days. Differences in growth rates reported in different studies can be attributed to environmental conditions that prevailed

during the crop growing phase, number of varieties studied, types of genotypes and source of varieties (Gedebo & Donkor, 2018; Ntundu *et al.*, 2006).

High variations in yields and yield traits found in this study are similar with what Shegro *et al*. (2013) as well as Valombola *et al*. (2019) reported in Bambara groundnut grown in South Africa and North-Central Namibia respectively. The variation in yield among different landraces could be attributed to genetic difference and ability to respond to environmental conditions (Reddy & Reddy, 2016; Zondi, 2012). Lack of significant differences in plant height corroborated the findings of Shegro *et al*. (2013) and Ntundu *et al*. (2006). The number of pods per plant found in the current study were considerably less than the figures found by Masindeni (2006) in Bambara groundnut cultivated in South Africa. This could be due to water stress during the reproductive phase as the experiments were rain-fed, which could explain the variations observed among landraces and their productivity and survival in a given environment (Mwale *et al*., 2007). These observations can be utilized in breeding programs (Mwale *et al*., 2007). Seed length ranged from 7.92 to 11.67 mm (Kangaru), 7.08 to 13.32 mm (Ishiara) and 8.03-11.85 mm (Kiamuringa). Seed width ranged from 7.11 to 9.78 mm (Kangaru), 7.48 to 9.49 mm (Ishiara) and 7.40-9.41 mm (Kiamuringa). This study's results differed from those of Mpotokwane *et al.* (2008) who found a range of 9.41 to 9.96 mm and 11.01 to 11.81 mm in seed width and seed length, respectively in Bambara groundnut grown in Botswana. Ntundu *et al*. (2006) found a range of 6.3-17.5 mm and 5.5 to 19.3 mm in length of seeds and seed diameter respectively in Bambara groundnut grown in Tanzania. The significant variations in length of seeds and seed width noted in the current study could have resulted from the different seed shapes as earlier observed by Olanrewaju *et al*. (2021).

The landraces BG-110, BG-112, LU-122 and BG-109 had higher weight of 100 seeds compared to other landraces implying that the seeds were more compact and well filled which may be an indicator of higher nutrient use efficiency and tolerance to environmental factors such as soil moisture stress and high temperatures (Zhang *et al*., 2021). Yield range between 0.60 and 2.44 t ha^{-1} (Kangaru), 0.69 to 3.16 tonnes per hectare (Ishiara) and 0.84 to 5.01 tonnes per hectare (Kiamuringa), indicating that there could be significant genotypic effect in yield which can also be modified by the environmental factors. Despite Bambara groundnut having potential of producing up

to 3 tons ha^{-1} (Mohammed *et al*., 2018), yields as low as 0.65 to 0.85 tons ha^{-1} (Majola *et al.*, 2021) and 2.9 tons ha^{-1} (Chandra *et al.*, 2017) have been reported. Low yields may result from poor adoption of improved agronomic practices and genotypic factors (Majola *et al*., 2021).

The significant agro-morphological variation that was observed between different seasons and experimental sites on most of the evaluated traits was an indication that the performance of Bambara groundnut may be considerably impacted by the environmental conditions. The same finding was noted by Khan *et al*. (2021b) who found significant variation for each agronomic variables excluding plant height in 15 Bambara groundnut studied in Malaysia. The significant location effects observed were significant for all quantitative traits can be ascribed to heterogeneity of the three study sites in terms of rainfall, temperature and soil conditions hence the need to assess genotypes in varied environments. Plant genotypes evaluated in different locations over years have been known to be affected by soil fertility, climatic factors and pests and diseases (Olanrewaju *et al.*, 2021).

Discriminant analysis showed that there was an observed overlap of the landraces in Kangaru and Kiamuringa, demonstrating that they had close proximity in terms of their influence to the performance of genotypes. The differences in soil types could have caused differences in performance of Bambara groundnut landraces. Humic Nitisols and Cambisols dominant in Kangaru and Kiamuringa respectively are characterized by high to moderate fertility making them suitable for agricultural uses (Lotse Tedontsah *et al*., 2022; Margaret *et al*., 2019). This could have caused the genotypes to perform more or less similarly. Acrisols and Ferrasols found in Ishiara are characterized by low fertility due to aluminium toxicity (Eckert *et al*., 2023).

Assessing genotype and environment interactions (GEI) interactions is important in identifying high performing landraces suitable for a particular ecological zone. Particular Bambara groundnut landrace elicited different results to each variable at different study sites and seasons suggesting the existence of genotype and environment interactions (GEI). Environmental conditions have been known to affect expression of quantitative variables in variants of beans hence the genotype that performs well in one environment may not do well in another (Arteaga *et al*., 2019). This means that specific

varieties must be developed for cultivation at different agro-ecological areas (Arteaga *et al*., 2019). Plant breeders consider yield and yield components important in identifying superior cultivars in Bambara groundnut (Khan *et al*., 2021a). Genotypes with stable yields in diverse environments are highly acceptable by plant breeders as they lower the risk of yield loss due to unfavourable weather (Khan *et al.* 2021a).

Correlation matrix showed that yield has positive and significant correlation with weight of 100 seeds and number of seeds. Similar observation was reported by Esan *et al.* (2023); Karikari & Tabona (2004) but Olanrewaju *et al*. (2021) reported divergent observation of negative correlation between the yields and the number of seeds. The positive correlations in several agro-morphological traits observed in this study suggest that improving one trait will have positive effect on the associated variables in plant breeding (Shegro *et al*., 2013). Therefore, some traits can be effectively used to select other variables. Negative significant correlation observed between several variables studied, showed that improvement of one desirable trait does not necessarily improve another trait hence improvements of these traits should be done separately.

5.2 Nutritional and phytochemical composition of Bambara groundnut

The Bambara groundnuts that were evaluated in this study had a significant variation in their mineral, proximate, and phytochemical contents. The landraces' moisture content varied between 3.467% to 6.238%. This value was less than that reported by Olaleye *et al*. (2013), which varied from 5.23 to 9.23g/100g. Yao *et al.* (2015) found moisture level of Bambara groundnut to be 11.7%. The seeds for the landraces KS-116, LU-123 and LU-124 are likely to have a reduced chances of being damaged by pests resulting in an extended shelf life after harvest (Afzal *et al*., 2019). On the other hand, the ash content observed among the tested landraces in this study was comparable to the values reported in similar previous studies (Jideani & Jideani, 2021; Murevanhema & Jideani, 2013; Nti, 2009). The low ash content of Bambara groundnut seeds indicated low level of inorganic substances in the sample with minerals being the main components (Ismail, 2017).

Bambara groundnut is known to be rich in high quality protein compared to other legumes such as cowpea (16.85%), pigeon pea (16.43%) and chickpea (15-22%) (James *et al*., 2020; Madurapperumage *et al*., 2021). The crude protein levels observed in this

study were comparable to those observed in velvet bean (Vadivel & Janardhanan, 2000) which reportedly contained 20.2 to 29.3%. However, the genotypes in this study had relatively higher crude protein content than the documented content for Bambara groundnuts (Mayes *et al*., 2019). Variation in the protein composition among different studies could be attributed to environmental conditions, genetics (Shinda *et al*., 2022) and also the differences in techniques of estimations for instance nitrogen conversion factor (Mubaiwa *et al*., 2018). Like other legumes, Bambara groundnuts is lysine-rich and methionine-poor, making it a good blend to cereals like maize that often have sufficient methionine but low lysine content (Boye *et al*., 2010).

The content of crude fat in the tested Bambara groundnut landraces was relatively higher than those found in cereals though may not be adequate to be utilized as oil source (Brough *et al*., 1993). However, Mabhaudhi *et al*. (2019) reported that a tribe in Congo was successfully extracting oil from Bambara seeds. Even so, the levels of crude fat reported in Bambara groundnut would not make them to be classified together with other oil rich legumes such as soybeans with around 19.5% and groundnut with 25% fat content (Duodu & Apea-Bah, 2017). The results from the present study showed that the landrace, BS-114, with dark colored seeds had the highest protein content of 26% but the lowest fat content of 4.56%. Correlation matrix also showed that fat content and protein were negatively correlated. Nti, (2009) also observed highest levels of crude protein and lowest levels of fat in dark variants (red and black) of Bambara groundnut and concluded that protein levels are negatively correlated to fat content (Nti, 2009).

Further characterization of the nutritional components showed that all the landraces had considerable amount of minerals higher than the mineral levels reported in other legumes that are mostly consumed such as mung beans (Hussin *et al*., 2020). According to Olaleye *et al*. (2013), potassium, iron, zinc, phosphorus and magnesium are the most dominant mineral elements found in Bambara groundnut seeds. These nutrients are crucial, especially in economically underdeveloped countries where there is a frequent consumption of cereals, making Bambara groundnut an excellent choice for such regions. The elements that induce variations in mineral in similar species of plants include genetic make-up, soil fertility, and the geographic origin of landraces (Gerrano *et al*., 2022). Although the measured potassium levels were higher than those present in widely eaten legumes like mung beans, they were lower than those found in other

Bambara groundnuts as reported by Dansi *et al*. (2012) as well as Chandra *et al*. (2017). According to Ekmekcioglu *et al*. (2016), potassium also lowers blood pressure, vasoconstriction, and serves as a vasodilator in addition to maintaining the body's alkaline-acid balance (Gerrano *et al*., 2022).

The zinc levels in the Bambara groundnut seeds in this current study were greater than those reported by Olaleye *et al*. (2013) in other Bambara groundnuts, but significantly lower than those reported by Murevanhema & Jideani, (2013). In particular, iron is crucial in the blood's production of haemoglobin (Gerrano *et al*., 2022). The findings also revealed that sodium concentration across the examined landraces varied greatly, ranging from 25.16 to 129.67 mg/100g. Chandra *et al*. (2017) reported a value of 75.25mg of sodium in Bambara groundnut grown in India. It is recommended that adults should consume not more than 6g of sodium in a day (Kenten *et al*., 2013) and high levels of sodium in the body is a health risk as it may cause problems such as cardiovascular diseases (Chandra *et al*., 2017). Therefore, the sodium content in Bambara groundnut is low enough to cause health risks.

The mean value of tannins observed in this study (ranging from 0.011 - 0.037 mg/g) was comparable with 0.039 mg/g and 0.046 mg/g reported by Ijarotimi & Esho (2009) and Mazahib *et al*. (2013) among Bambara seeds cultivated in Nigeria and Sudan, respectively, but lower than 4.5 and 15 CE $^{g-1}$ reported by Nti (2009). Although tannins are important in defence to seeds grown in unfavourable environments (Xu & Chang, 2007), they lower the palatability of the crops by causing bitter taste in plants (Rauf *et al*., 2019). Low tannins ensure absorption of essential micronutrients and digestion of protein (Khazaei *et al*., 2019). The flavonoids content observed among the Bambara groundnut landraces was much lower than what was reported by Olaleye *et al.* (2013) but the saponins content corroborated the findings of Olaleye *et al.* (2013). Alkaloids content observed this study was comparable to what was reported by Mbagwu *et al.* (2011) in Bambara groundnut in Eastern Nigeria. Alkaloids have been reported to have anti-cancer activity (Gupta *et al*., 2015) anti-malarial activity (Onguéné *et al*., 2013) and helps to prevent stroke (Kumar & Khanum, 2012).

The diversity among the 17 genotypes were further assessed using cluster analysis based on their nutritional and phytochemical composition. The high percentage of

diversity observed between different clusters and the low diversity observed within clusters was a good indication that the nutritional and phytochemical components can be successfully used to discriminate between different Bambara groundnut genotypes. The cluster analysis did not group the landraces based on their place of origin indicating that the landraces may have a wider environmental adaptability hence can be widely exploited by the farmers based on the nutritional and phytochemical preferences. This observation was also supported by the Principal Component Analysis (PCA) where the genotypes were separated based on the components that captured the largest share of explained variance. The PCA also uses factor loading to show which features correlate with the most important components. Therefore, both cluster analysis and PCA are useful tools in selecting landraces with desirable traits that can be exploited in a plant breeding program.

Correlation analysis helps in determining the relationship between traits and it's useful in assessing trait combinations during selection. The study showed that saponins were positively correlated to tannins and flavonoids. Positive correlation between the phytochemical is especially important when the objective is to improve the pharmaceutical properties of the genotypes. A negative correlation was observed between the alkaloids and potassium content as well as between flavonoids and sodium content. This means that lowering the level of alkaloids would increase the level of potassium and increasing the level of flavonoids would lower the content of sodium and vice-versa. The flavonoid content was found to positively correlated to iron indicating that the two traits may co-segregate hence enabling their combined selection. This may also be possible when targeting a high protein content with low fat content since the two traits were found to be negatively correlated. However, the protein content was positively correlated to the sodium content indicating that improvement of the protein content using conventional breeding methods without increasing sodium content would be difficult unlike for iron which was negatively correlated to sodium. Lack of significant correlation between various traits was an indication that such traits may not be linked hence their selection should be considered on single trait basis.

5.3 Conclusion

This study established that there exists significant agro-morphological diversity among Bambara groundnut landraces available in Kenya. This diversity can be utilized in

genetic improvement of the crop to improve its economic potential. Although different Bambara groundnut landraces responded differently to different agro-ecological conditions, most of the landraces performed appreciably well and therefore the economic potential within the crop can be termed as enormous. Therefore, adoption of Bambara groundnut as a climate smart crop can have a significant impact on improving nutritional and food security in Embu County and in other locations with similar climatic conditions. However, more testing of the crop in diverse agro-ecological conditions may be useful in order to identify the most suitable landraces for different areas. This study also confirmed that the Bambara groundnut landraces studied were rich in nutrients mainly minerals and protein and can be an excellent source of minerals and plant-based protein in the human nutrition improvement programs. The observed diversity in the proximate, nutritional and phytochemical composition of the tested landraces provides the basis of genetic selection for enhanced nutritional and phytochemical composition of this high value legume.

5.4 Recommendations

The following recommendations have been made from this study based on the findings:

1. Although the tested landraces portrayed significant agro-morphological diversity, most of them performed appreciably well in the three sites in Embu County. BS-107, LU-122, LU-121, BS-134 and BS-144 are among the high yielding landraces identified and can be adopted for cultivation. The study therefore recommends promotion of Bambara groundnut production as a climate smart crop in Embu County and other dryland areas in Kenya where the crop can potentially grow.
2. The landraces with high nutritional value such as BG-125, BS-148 and BS-145, among others, are recommended to farmers for adoption.
3. The landraces with high levels of phytochemicals are recommended to pharmaceutical and nutraceutical industries for exploitation of their medicinal value. These may include BS-104 for flavonoids and MU-137 for saponins.
4. The nutritional value of landraces KS-108 LU-123 and BS-114 and should be enhanced by lowering the sodium in them.

5.5 Recommendation for further research

Characterization of Bambara groundnut landraces available in Kenya using molecular techniques is recommended to identify the genetic diversity within the crop and

possibly identify some more desirable genetic traits that could be utilized in programs for breeding to improve the crop. Genetic characterization could also assist in identification of less prevalent genotypes that may require enhanced conservation measures. In addition, more agronomic evaluation of the crop in more diverse agro-ecological conditions may be useful in order to identify the genetically stable genotypes and the most suitable landraces for different areas.

REFERENCES

Adeleke, O. R., Adiamo, O. Q., & Fawale, O. S. (2018). Nutritional, physicochemical, and functional properties of protein concentrate and isolate of newly-developed Bambara groundnut (*Vigna subterrenea* L.) cultivars. *Food Science & Nutrition*, *6*(1), 229–242.

Afzal, I., Zahid, S., & Mubeen, S. (2019). Tools and techniques of postharvest processing of food grains and seeds. In *Agronomic Crops* (pp. 583–604). Springer. https://doi.org/10.1007/978-981-32-9783-8_26.

Ahmad, N. (2012). *Bambara groundnut , The Crop for New Millennium: Molecular Techniques to Improve the Resiliency of Bambara groundnut* . LAP LAMBERT Academic Publishing.

Ajuang, C. O., Abuom, P. O., Bosire, E. K., Dida, G. O., & Anyona, D. N. (2016). Determinants of climate change awareness level in upper Nyakach Division, Kisumu County, Kenya. *SpringerPlus*, *5*(1), 1–20. https://doi.org/10.1186/s40064-016-2699-y.

Akin-Idowu, P. E., Gbadegesin, M. A., Orkpeh, U., Ibitoye, D. O., & Odunola, O. A. (2016). Characterization of grain amaranth (*Amaranthus spp.*) germplasm in South West Nigeria using morphological, nutritional, and random amplified polymorphic DNA (RAPD) analysis. *Resources*, *5*(1), 6.

Akpalu, M. M., Atubilla, I. A., & Oppong-Sekyere, D. (2013). Assessing the level of cultivation and utilization of Bambara groundnut (*Vigna subterranea* (L.) Verdc.) in the Sumbrungu community of Bolgatanga, Upper East Region, Ghana. *International Journal of Plant, Animal and Environmental Sciences*, *3*(3), 68–75.

Alake, C. O., Ayo-Vaughan, M. A., & Ariyo, J. O. (2015). Selection criteria for grain yield and stability in Bambara groundnut (*Vigna subterranean* (L) Verdc) landraces. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, *65*(5), 433–447.

Aliyu, S., Massawe, F., & Mayes, S. (2016). Genetic diversity and population structure of Bambara groundnut (*Vigna subterranea* (L.) Verdc.): synopsis of the past two decades of analysis and implications for crop improvement programmes. *Genetic Resources and Crop Evolution*, *63*(6), 925–943.

Amadou, H. I., Bebeli, P. J., & Kaltsikes, P. J. (2001). Genetic diversity in Bambara groundnut (*Vigna subterranea* L.) germplasm revealed by RAPD markers. *Genome*, *44*(6), 995–999. https://doi.org/10.1139/g01-096.

Amadou, H. I., Doumma, A., Katsileros, A., Zoubeirou, A. M., & Nourou, S. S. M. (2015). Agro-morphological variability in fourteen Bambara groundnut (*Vigna subterranean* (L.) Verdc.) morphotypes cultivated in Niger. *SAJB*, *3*, 774–781.

Amoa Onguéné, P., Ntie-Kang, F., Lifongo, L. L., Ndom, J. C., Sippl, W., & Mbaze, L. M. (2013). The potential of anti-malarial compounds derived from African medicinal plants. Part I: A pharmacological evaluation of alkaloids and terpenoids. *Malaria Journal*, *12*(1), 1–26. https://doi.org/10.1186/1475-2875-13-81.

Anchirinah, V. M., Yiridoe, E. K., & Bennett-Lartey, S. O. (2001). Enhancing sustainable production and genetic resource conservation of Bambara groundnut : a survey of indigenous agricultural knowledge systems. *Outlook on AGRICULTURE*, *30*(4), 281–288.

Arteaga, S., Yabor, L., Torres, J., Solbes, E., Muñoz, E., Díez, M. J., Vicente, O., & Boscaiu, M. (2019). Morphological and agronomic characterization of Spanish landraces of *Phaseolus vulgaris* L. *Agriculture*, *9*(7), 149.

Atoyebi, J. O., Osilesi, O., Abberton, M., Adebawo, O., & Oyatomi, O. (2018). Quantification of selected anti-nutrients and bioactive compounds in African Bambara groundnut (*Vigna subterranea* (L.) Verdc.). *Am J Food Nutr*, *6*(3), 88–95.

Atoyebi, J. O., Oyatomi, O., Osilesi, O., Adebawo, O., & Abberton, M. (2017a). Morphological characterisation of selected African accessions of Bambara groundnut (*Vigna subterranea* (L.) verdc.). *International Journal of Plant Research*, *7*(2), 29–35. https://doi.org/10.5923/j.plant.20170702.01.

Atsiaya, G. O., Gido, E. O., & Waluse Sibiko, K. (2023). Uptake of climate-smart agricultural practices among smallholder sorghum farmers in Busia County, Kenya. *Cogent Food & Agriculture*, *9*(1), 2204019.

Azam-Ali, S. N., Sesay, A., Karikari, S. K., Massawe, F. J., Aguilar-Manjarrez, J., Bannayan, M., & Hampson, K. J. (2001). Assessing the potential of an underutilized crop–a case study using Bambara groundnut. *Experimental Agriculture*, *37*(4), 433–472.

Basu, S., Roberts, J. A., Azam-Ali, S. N., & Mayes, S. (2007). Bambara groundnut . In *Pulses, Sugar and Tuber Crops* (pp. 159–173). Springer. https://doi.org/10.1007/978-3-540-34516-9_10.

Bonny, B. S., Dagou, S., Adjoumani, K., Koffi, K. E. G., Kouonon, L., & Sie, R. S. (2019). Evaluation of the diversity in qualitative traits of Bambara groundnut germplasm (*Vigna subterranea* (L.) Verdc.) of Côte d'Ivoire. *African Journal of Biotechnology*, *18*(1), 23–36.

Boye, J., Zare, F., & Pletch, A. (2010). Pulse proteins: Processing, characterization, functional properties and applications in food and feed. *Food Research International*, *43*(2), 414–431.

Brink, M., & Belay, G. (2006). *Plant resources of tropical Africa 1: cereals and pulses. PROTA Foundation, Wageningen, Netherlands*. Backhuys Publishers, Leiden, Netherlands/CTA, Wageningen, Netherlands.

Brough, S. H., Azam-Ali, S. N., & Taylor, A. J. (1993). The potential of Bambara groundnut (*Vigna subterranea*) in vegetable milk production and basic protein functionality systems. *Food Chemistry*, *47*(3), 277–283. https://doi.org/10.1016/0308-8146(93)90161-8.

Caleb, A., Helida, O., Amolo, E., & Benard, M. (2022). Morphological Identification of Edible Termites (Isoptera) in Luanda Sub-County, Kenya. *Advances in Entomology*, *10*(2), 159–174. https://doi.org/OI: 10.4236/ae.2022.102012.

Chai, H. H., Massawe, F., & Mayes, S. (2016). Effects of mild drought stress on the morpho-physiological characteristics of a Bambara groundnut segregating population. *Euphytica*, *208*(2), 225–236.

Chandra, K., Nandini, R., Pranesh, C. B. K., & Gobu, R. (2017). Improving Nutritional Security of India through a potential underutilized legume-Bambara groundnut (*Vigna subterranea* (L.) Verdc.). *Environ. Ecol*, *35*(2), 606–610.

Chelangat, M., Muturi, P., Gichimu, B., Gitari, J., & Mukono, S. (2023). Nutritional and Phytochemical Composition of Bambara groundnut (*Vigna subterranea* [L.] Verdc) Landraces in Kenya. *International Journal of Agronomy*, *2023*.

Coyne, C., & McGee, R. (2013). Lentil. In *Genetic and Genomic Resources of Grain Legume Improvement* (pp. 157–180). Elsevier.

Daffodil, E. D., Tresina, P. S., & Mohan, V. R. (2015). Nutritional and antinutritional assessment of *Mucuna pruriens* (L.) DC var. utilis (Wall ex. Wight) Bak. Ex Burck and *Mucuna deeringiana* (Bort) Merril: An underutilized tribal pulse. *International Food Research Journal*, *23*(4), 1501.

Dansi, A., Vodouhè, R., Azokpota, P., Yedomonhan, H., Assogba, P., Adjatin, A., Loko, Y. L., Dossou-Aminon, I., & Akpagana, K. (2012). Diversity of the neglected and underutilized crop species of importance in Benin. *The Scientific World Journal*, *2012*. https://doi.org/10.1100/2012/932947.

Diwani, T. N., Asch, F., Becker, M., & Mussgnug, F. (2013). Characterizing farming systems around Kakamega Forest, Western Kenya, for targeting soil fertility–enhancing technologies. *Journal of Plant Nutrition and Soil Science*, *176*(4), 585–594. https://doi.org/10.1002/jpln.201200036.

Duodu, K. G., & Apea-Bah, F. B. (2017). African legumes: nutritional and health-promoting attributes. In *"African legumes: nutritional and health-promoting attributes." Gluten-Free Ancient Grains. Woodhead Publishing, 2017. 223-269.* (pp. 223–269). Elsevier. https://doi.org/10.1016/j.heliyon.2022.e09024.

Eckert, D. J., Martins, A. P., Vian, A. L., Pesini, G., Alves, L. A., Flores, J. P. M., Filippi, D., Tiecher, T. L., Fink, J. R., & Bredemeier, C. (2023). Single superphosphate replacing agricultural gypsum: short-term effect on grain yield and soil chemical properties in subtropical soils under no-tillage. *Archives of Agronomy and Soil Science*, *69*(11), 1973–1989.

Egbe, M. O., Alhassan, G. A., & Ijoyah, M. (2013). Nodulation, nitrogen yield and fixation by Bambara groundnut (*Vigna subterranea* (L.) Verdc.) landraces intercropped with cowpea and maize in Southern Guinea Savanna of Nigeria. *Agricultural Science*, *1*(4), 15–28.

Ekmekcioglu, C., Elmadfa, I., Meyer, A. L., & Moeslinger, T. (2016). The role of dietary potassium in hypertension and diabetes. *Journal of Physiology and Biochemistry*, *72*(1), 93–106. https://doi.org/10.1007/s13105-015-0449-1.

Esan, V. I., Oke, G. O., & Ogunbode, T. O. (2023). Genetic variation and characterization of Bambara groundnut [*Vigna subterranea* (L.) verdc.] accessions under multi-environments considering yield and yield components performance. *Scientific Reports*, *13*(1), 1498.

FSSAI, M. (2015). Manual of methods of analysis of foods. *Method*, *16*, 56–61.

Gachimbi, L. N. (2002). *Technical report of soil survey and sampling results: Embu–Mbeere Districts, Kenya, Land Use Change Impacts & Dynamics (LUCID).* Project Working Paper, International Livestock Research Institute, Nairobi.

Gbaguidi, A. A., Dansi, A., Dossou-Aminon, I., Gbemavo, D., Orobiyi, A., Sanoussi, F., & Yedomonhan, H. (2018). Agromorphological diversity of local Bambara groundnut (*Vigna subterranea* (L.) Verdc.) collected in Benin. *Genetic Resources and Crop Evolution*, *65*, 1159–1171.

Gedebo, A., & Donkor, E. F. (2018). Morphological Characterization and Genetic Variability among Bambara groundnut (*Vigna subterranean* L. Verdc.) Accessions of Ghana. *Journal of Science & Development*, *6*, 1.

Gemede, H. F., & Ratta, N. (2014). Antinutritional factors in plant foods: Potential health benefits and adverse effects. *International Journal of Nutrition and Food Sciences*, *3*(4), 284–289.

Gerrano, A. S., Lubinga, M. H., & Bairu, M. W. (2022). Genetic resources management, seed production constraints and trade performance of orphan crops in Southern Africa: A case of Cowpea. *South African Journal of Botany*, *146*, 340–347. https://doi.org/10.1016/j.sajb.2021.11.007.

Gichimu, B. M., Owuor, B. O., Mwai, G. N., & Dida, M. M. (2009). *Morphological characterization of some wild and cultivated watermelon (Citrullus sp.) accessions in Kenya*. *4*.

Gupta, A. P., Pandotra, P., Kushwaha, M., Khan, S., Sharma, R., & Gupta, S. (2015). Alkaloids: A source of anticancer agents from nature. *Studies in Natural Products Chemistry*, *46*, 341–445. https://doi.org/10.1016/B978-0-444-63462-7.00009-9.

Halimi, R. A., Barkla, B. J., Mayes, S., & King, G. J. (2019). The potential of the underutilized pulse Bambara groundnut (*Vigna subterranea* (L.) Verdc.) for nutritional food security. *Journal of Food Composition and Analysis*, *77*, 47–59. https://doi.org/10.1016/j.jfca.2018.12.008.

Harouna, D. V., Venkataramana, P. B., Ndakidemi, P. A., & Matemu, A. O. (2018). Under-exploited wild Vigna species potentials in human and animal nutrition: a review. *Global Food Security*, *18*, 1–11. https://doi.org/10.1016/j.gfs.2018.06.002.

Hillocks, R. J., Bennett, C., & Mponda, O. M. (2012). Bambara nut: A review of utilisation, market potential and crop improvement. *African Crop Science Journal*, *20*(1).

Hussin, H., Gregory, P. J., Julkifle, A. L., Sethuraman, G., Tan, X. L., Razi, F., & Azam-Ali, S. N. (2020). Enhancing the nutritional profile of noodles with Bambara groundnut (*Vigna subterranea*) and moringa (*Moringa oleifera*): A food system approach. *Frontiers in Sustainable Food Systems*, *4*, 59.

Ijarotimi, O. S., & Esho, T. R. (2009). Comparison of nutritional composition and anti-nutrient status of fermented, germinated and roasted Bambara groundnut seeds (*Vigna subterranea*). *British Food Journal*.

IPGRI, BAMNET, IITA. (2000). BAMNET (2000) Descriptors for Bambara groundnut (*Vigna subterranea*), International Plant Genetic Resources Institute, Rome, Italy; International Institute of Tropical Agriculture, Ibadan, Nigeria. *The International Bambara groundnut Network, Germany*.

Ismail, B. P. (2017). Ash content determination. In *Food analysis laboratory manual* (pp. 117–119). Springer.

Jaetzold, R., Schmidt, H., Hornetz, B., & Shisanya, C. (2006). Farm management handbook of Kenya Vol. II–Natural Conditions and Farm Management Information–2nd Edition part c; East Kenya Subpart C1 Eastern Province. *Ministry of Agriculture, Nairobi, Kenya*.

James, S., Nwabueze, T. U., Onwuka, G. I., Ndife, J., & Usman, M. A. (2020). Chemical and nutritional composition of some selected lesser known legumes indigenous to Nigeria. *Heliyon*, *6*(11).

Jiang, Y., Lindsay, D. L., Davis, A. R., Wang, Z., MacLean, D. E., Warkentin, T. D., & Bueckert, R. A. (2020). Impact of heat stress on pod-based yield components in field pea (*Pisum sativum* L.). *Journal of Agronomy and Crop Science*, *206*(1), 76–89.

Jideani, V. A., & Jideani, A. I. O. (2021). Ethnonutritional and ethnomedicinal uses of Bambara groundnut . In *Bambara groundnut : Utilization and Future Prospects* (pp. 49–60). Springer.

Karikari, S. K., & Tabona, T. T. (2004). Constitutive traits and selective indices of Bambara groundnut (*Vigna subterranea* (L) Verdc) landraces for drought tolerance under Botswana conditions. *Physics and Chemistry of the Earth, Parts A/B/C*, *29*(15–18), 1029–1034.

Karunaratne, A., Crout, N., Azam-Ali, S., Mayes, S., Steduto, P., & Izzi, G. (2009). Modelling The Response Of Bambara groundnut: A Key Underutilised Crop In Agricultural Systems. *ECMS*, 841–847.

Kendabie, P., Jorgensen, S. T., Massawe, F., Azam-Ali, S., & Mayes, S. (2016). Daylength effects on growth and seed production efficiency in Bambara groundnut (*Vigna subterranea* L.). *3rd International Conference on Neglected and Underutilized Species*, 28.

Kenten, C., Boulay, A., & Rowe, G. (2013). Salt. UK consumers' perceptions and consumption patterns. *Appetite*, *70*, 104–111. https://doi.org/10.1016/j.appet.2013.06.095.

Khaliqi, A., Rafii, M. Y., Mazlan, N., Jusoh, M., & Oladosu, Y. (2021). Genetic analysis and selection criteria in Bambara groundnut accessions based yield performance. *Agronomy*, *11*(8), 1634.

Khan, M. M. H., Rafii, M. Y., Ramlee, S. I., Jusoh, M., & Al-Mamun, M. (2021). Bambara groundnut (*Vigna subterranea* L. Verdc): A crop for the new millennium, its genetic diversity, and improvements to mitigate future food and nutritional challenges. In *Sustainability (Switzerland)* (Vol. 13, Issue 10). MDPI AG. https://doi.org/10.3390/su13105530.

Khan, M. M. H., Rafii, M. Y., Ramlee, S. I., Jusoh, M., & Al Mamun, M. (2021a). AMMI and GGE biplot analysis for yield performance and stability assessment of selected Bambara groundnut (*Vigna subterranea* L. Verdc.) genotypes under the multi-environmental trials (METs). *Scientific Reports*, *11*(1), 22791.

Khan, M. M. H., Rafii, M. Y., Ramlee, S. I., Jusoh, M., & Al Mamun, M. (2021b). Genetic analysis and selection of Bambara groundnut (*Vigna subterranea* [L.] Verdc.) landraces for high yield revealed by qualitative and quantitative traits. *Scientific Reports*, *11*(1), 7597.

Khan, M. M. H., Rafii, M. Y., Ramlee, S. I., Jusoh, M., & Mamun, A. (2020). Genetic variability, heritability, and clustering pattern exploration of Bambara groundnut (*Vigna subterranea* L. Verdc) accessions for the perfection of yield and yield-related traits. *BioMed Research International*, *2020*.

Khazaei, H., Purves, R. W., Hughes, J., Link, W., O'Sullivan, D. M., Schulman, A. H.,

Björnsdotter, E., Geu-Flores, F., Nadzieja, M., & Andersen, S. U. (2019). Eliminating vicine and convicine, the main anti-nutritional factors restricting faba bean usage. *Trends in Food Science & Technology*, *91*, 549–556. https://doi.org/10.1016/j.tifs.2019.07.051.

Kiarie, S. W., Okoth, S., Gikungu, M., & Imbahale, S. S. (2022). Characterization of Pathogenic Fungi Infecting *Citrullus lanatus* in Different Agroecological Regions of Embu County, Kenya. *Journal of Agriculture and Sustainability*, *15*.

Kiboi, M. N., Ngetich, F. K., Mucheru-Muna, M. W., Diels, J., & Mugendi, D. N. (2021). Soil nutrients and crop yield response to conservation-effective management practices in the sub-humid highlands agro-ecologies of Kenya. *Heliyon*, *7*(6), e07156.

Kiema, A. M., Kitilit, J. K., Nthakanio, P. N., Kios, D. K., & Rachuonyo, H. (2020). The Effect of Upgrading Indigenous Goat Breeds with German Alpine on Milk Yields at Manyatta Division of Embu County. *African Journal of Education, Science and Technology*, *6*(1), 291–297.

Koné, M., Paice, A. G., & Touré, Y. (2011). Bambara groundnut [*Vigna subterranea* (L.) Verdc.(Fabaceae)] usage in human health. In *Nuts and Seeds in Health and Disease Prevention* (pp. 189–196). Elsevier. https://doi.org/10.1016/B978-0-12-375688-6.10022-2.

Kumar, G. P., & Khanum, F. (2012). Neuroprotective potential of phytochemicals. *Pharmacognosy Reviews*, *6*(12), 81. https://doi.org/10.4103/0973-7847.99898.

Lotse Tedontsah, V. P., Mbog, M. B., Ngon Ngon, G. F., Edzoa, R. C., Tassongwa, B., Bitom, D., & Etame, J. (2022). Physicochemical properties and fertility assessment of soils in foumban (west Cameroon). *Applied and Environmental Soil Science*, *2022*.

Mabhaudhi, T., & Modi, A. T. (2013). Growth, phenological and yield responses of a Bambara groundnut (*Vigna subterranea* (L.) Verdc.) landrace to imposed water stress under field conditions. *South African Journal of Plant and Soil*, *30*(2), 69–79.

Mabhaudhi, T., Petrova, V. G., Hlahla, F., Mayes, S., Massawe, S., Nhamo, L., & Modi, A. T. (2019). Prospects of orphan crops in climate change. *Planta*, *250*(3), 695–708. https://doi.org/10.1007/s00425-019-03129-y.

Machani, M. G., Ochomo, E., Sang, D., Bonizzoni, M., Zhou, G., Githeko, A. K., Yan, G., & Afrane, Y. A. (2019). Influence of blood meal and age of mosquitoes on susceptibility to pyrethroids in Anopheles gambiae from Western Kenya. *Malaria Journal*, *18*(1), 1–9.

Madurapperumage, A., Tang, L., Thavarajah, P., Bridges, W., Shipe, E., Vandemark, G., & Thavarajah, D. (2021). Chickpea (*Cicer arietinum* L.) as a source of essential fatty acids–a biofortification approach. *Frontiers in Plant Science*, *12*, 734980.

Majola, N. G., Gerrano, A. S., & Shimelis, H. (2021). Bambara groundnut (*Vigna subterranea* [L.] Verdc.) Production, Utilisation and Genetic Improvement in Sub-Saharan Africa. *Agronomy*, *11*(7), 1345. https://doi.org/10.3390/agronomy11071345.

Makilla, D. M. (2020). *Characterization And Control Of Pathogenic Parasites in Nile*

Tilapia (Oreochromis Niloticus Linnaeus 1758) in Fish-Farming Systems in Bungoma County, Kenya. School of Pure and Applied Sciences, Kenyatta University.

Margaret, O., Nwadi, M., Okonkwo, T. M., Nwadi, O. M. M., Uchegbu, N., & Okonkwo, T. M. (2019). Effect of processing methods on the antinutrient reduction of Bambara groundnut : A review. In *Sky Journal of Food Science* (Vol. 7, Issue 3). http://www.skyjournals.org/SJFS.

Masindeni, D. R. (2006). *Evaluation of Bambara groundnut (Vigna subterranea) for yield stability and yield related characteristics*. University of the Free State.

Massawe, F. J., Mwale, S. S., Azam-Ali, S. N., & Roberts, J. A. (2005). Breeding in Bambara groundnut (*Vigna subterranea* (L.) Verdc.): strategic considerations. *African Journal of Biotechnology*, *4*(6), 463–471.

Mayes, S., Ho, W. K., Chai, H. H., Gao, X., Kundy, A. C., Mateva, K. I., Zahrulakmal, M., Hahiree, M. K. I. M., Kendabie, P., & Licea, L. C. S. (2019). Bambara groundnut : An exemplar underutilised legume for resilience under climate change. *Planta*, *250*(3), 803–820. https://doi.org/10.1007/s00425-019-03191-6.

Mayes, S., Massawe, F. J., Alderson, P. G., Roberts, J. A., Azam-Ali, S. N., & Hermann, M. (2012). The potential for underutilized crops to improve security of food production. *Journal of Experimental Botany*, *63*(3), 1075–1079.

Mazahib, A. M., Nuha, M. O., Salawa, I. S., & Babiker, E. E. (2013). Some nutritional attributes of Bambara groundnut as influenced by domestic processing. *International Food Research Journal*, *20*(3), 1165.

Mbagwu, F., Okafor, V. U., & Ekeanyanwu, J. (2011). Phytochemical screening on four edible legumes (*Vigna subterranean, Glycine max, Arachis hypogea*, and *Vigna uniguiculata*) found in eastern Nigeria. *African Journal of Plant Science*, *5*(6), 370–372.

Mbosso, C., Boulay, B., Padulosi, S., Meldrum, G., Mohamadou, Y., Berthe Niang, A., Coulibaly, H., Koreissi, Y., & Sidibé, A. (2020). Fonio and Bambara groundnut value chains in mali: issues, needs, and opportunities for their sustainable promotion. *Sustainability*, *12*(11), 4766.

Minka, S. R., & Bruneteau, M. (2000). Partial chemical composition of Bambara pea [*Vigna subterranea* (L.) Verde]. *Food Chemistry*, *68*(3), 273–276. https://doi.org/10.1016/S0308-8146(99)00186-7.

Mogale, T. E. (2018). *Multi-Location Field Evaluation of Bambara groundnut (Vigna subterranean (L) Verdc) for Agronomic Performance and Seed Protein.*

Mohammed, M. S., Shimelis, H. A., & Laing, M. D. (2016). Phenotypic characterization of diverse Bambara groundnut (*Vigna subterranea* [L.] Verdc.) germplasm collections through seed morphology. *Genetic Resources and Crop Evolution*, *63*(5), 889–899.

Mohammed, M. S., Shimelis, H. A., & Laing, M. D. (2018). *Preliminary investigation on some agronomic and morphological variations of within and between Bambara groundnut landraces*.

Mpotokwane, S. M., Gaditlhatlhelwe, E., Sebaka, A., & Jideani, V. A. (2008). Physical properties of Bambara groundnuts from Botswana. *Journal of Food Engineering*,

89(1), 93–98.

Mubaiwa, J., Fogliano, V., Chidewe, C., Bakker, E. J., & Linnemann, A. R. (2018). Utilization of Bambara groundnut (*Vigna subterranea* (L.) Verdc.) for sustainable food and nutrition security in semi-arid regions of Zimbabwe. *PLoS One*, *13*(10), e0204817. https://doi.org/10.1371/journal.pone.0204817.

Mubaiwa, J., Fogliano, V., Chidewe, C., & Linnemann, A. R. (2017). Hard-to-cook phenomenon in Bambara groundnut (*Vigna subterranea* (L.) Verdc.) processing: Options to improve its role in providing food security. In *Food Reviews International* (Vol. 33, Issue 2, pp. 167–194). Taylor and Francis Inc. https://doi.org/10.1080/87559129.2016.1149864.

Muimba-Kankolongo, A. (2018). *Food Crop Production by Smallholder Farmers in Southern Africa: Challenges and Opportunities for Improvement*. Academic Press.

Mukwabi, D. M., Okemo, P. O., Otieno, S. O., Oduor, R. O., & Macharia, C. M. (2019). Temperature and ph influence on bacterial pathogens infecting farmed Nile tilapia in aquaculture systems in Bungoma County, Kenya. *International Journal of Fisheries and Aquatic Studies*, *7*(1), 190–197.

Murevanhema, Y. Y., & Jideani, V. A. (2013). Potential of Bambara groundnut (*Vigna subterranea* (L.) Verdc) Milk as a Probiotic Beverage—A Review. *Critical Reviews in Food Science and Nutrition*, *53*(9), 954–967. https://doi.org/10.1080/10408398.2011.574803.

Mwakha, F. A., Gichimu, B. M., Neondo, J. O., Kamau, P. K., Odari, E. O., Muli, J. K., & Budambula, N. L. M. (2020). Agro-morphological characterization of Kenyan Slender Leaf (*Crotalaria brevidens* and *C. ochroleuca*) accessions. *International Journal of Agronomy*, *2020*, 1–10.

Mwale, S. S., Azam-Ali, S. N., & Massawe, F. J. (2007). Growth and development of Bambara groundnut (*Vigna subterranea*) in response to soil moisture: 1. Dry matter and yield. *European Journal of Agronomy*, *26*(4), 345–353. https://doi.org/10.1016/j.eja.2006.09.007.

Ndidi, U. S., Ndidi, C. U., Aimola, I. A., Bassa, O. Y., Mankilik, M., & Adamu, Z. (2014). Effects of processing (boiling and roasting) on the nutritional and antinutritional properties of Bambara groundnuts (*Vigna subterranea* [L.] Verdc.) from Southern Kaduna, Nigeria. *Journal of Food Processing*, *2014*.

Nerdy, B. (2018). Determination of sodium, potassium, magnesium, and calcium minerals level in fresh and boiled broccoli and cauliflower by atomic absorption spectrometry. *IOP Conference Series: Materials Science and Engineering*, *288*(1).

Ngailo, S., Shimelis, H., Sibiya, J., Mtunda, K., & Mashilo, J. (2019). Genotype-by-environment interaction of newly-developed sweet potato genotypes for storage root yield, yield-related traits and resistance to sweet potato virus disease. *Heliyon*, *5*(3), e01448.

Ngomuo, M., Stoilova, T., Feyissa, T., & Ndakidemi, P. A. (2017). Characterization of morphological diversity of jute mallow (*Corchorus* spp.). *International Journal of Agronomy*, *2017*.

Nti, C. A. (2009). Effects of Bambara groundnut (*Vigna subterranea*) variety and processing on the quality and consumer appeal for its products. *International Journal of Food Science & Technology*, *44*(11), 2234–2242.

https://doi.org/10.1111/j.1365-2621.2009.02064.x.

Ntundu, W. H., Shillah, S. A., Marandu, W. Y. F., & Christiansen, J. L. (2006). Morphological diversity of Bambara groundnut [*Vigna subterranea* (L.) Verdc.] landraces in Tanzania. *Genetic Resources and Crop Evolution*, *53*(2), 367–378. https://doi.org/10.1007/s10722-004-0580-2.

Obadoni, B. O., & Ochuko, P. O. (2001). Phytochemical studies and comparative efficacy of the crude extracts of some haemostatic plants in Edo and Delta States of Nigeria. *Global Journal of Pure and Applied Sciences*, *8*(2), 203–208. https://doi.org/10.4314/gjpas.v8i2.16033.

Ochwang'i, D. O., Kimwele, C. N., Oduma, J. A., Gathumbi, P. K., Mbaria, J. M., & Kiama, S. G. (2014). Medicinal plants used in treatment and management of cancer in Kakamega County, Kenya. *Journal of Ethnopharmacology*, *151*(3), 1040–1055. https://doi.org/10.1016/j.jep.2013.11.051.

Olaleye, Adeyeye, & Adesina. (2013). Chemical composition of Bambara groundnut (*V. subterranea* L. Verdc) seed parts. *Bangladesh Journal of Scientific and Industrial Research*, *48*(3), 167–178. https://doi.org/10.3329/bjsir.v48i3.17325.

Olanrewaju, O. S., Oyatomi, O., Babalola, O. O., & Abberton, M. (2021). Genetic diversity and environmental influence on growth and yield parameters of Bambara groundnut . *Frontiers in Plant Science*, 2967.

Olayinka, B. U., & Etejere, E. O. (2018). Proximate and Chemical Compositions of Watermelon (*Citrullus lanatus* (Thunb.) Matsum and Nakai cv Red and Cucumber (*Cucumis sativus* L. cv Pipino). *International Food Research Journal*, *25*(3).

Oluoch, W. A., Oindo, B. O., & Abuom, P. (2017). *Effects of Locations On-and Off-Epigeal Termitaria on Vegetation Lifeforms in Katolo Sub-Location of Kisumu County, Kenya*.

Oria, P. A., Moshi, V., Odero, J. I., Ekodir, S., Monroe, A., Harvey, S. A., Ochomo, E., & Piccinini Black, D. (2021). A retail audit of mosquito control products in Busia County, western Kenya. *Malaria Journal*, *20*(1), 1–12. https://doi.org/10.1186/s12936-021-03695-1.

Ouedraogo, M., Ouedraogo, J. T., Tignere, J. B., Bilma, D., Dabire, C. B., & Konate, G. (2008). Characterization and evaluation of accessions of Bambara groundnut (*Vigna subterranea* (L.) Verdcourt) from Burkina Faso. *Sciences & Nature*, *5*(2), 191–197.

Owino, M. H., Gichimu, B. M., & Muturi, P. W. (2020). Agro-morphological characterization of horned melon (*Cucumis metuliferus*) accessions from selected agro-ecological zones in Kenya. *Australian Journal of Crop Science*, *14*(9), 1487–1496.

Oyeyinka, A. T., Pillay, K., & Siwela, M. (2017). Consumer awareness and acceptability of Bambara groundnut as a protein source for use in complementary foods in rural KwaZulu-Natal. *South African Journal of Clinical Nutrition*, *30*(4), 87–92. https://doi.org/10.1080/16070658.2017.1282581.

Rahman, A., & Shah, S. M. A. (2019). Genotype× Environment interaction for yield and associated traits in rice. *Sarhad J. Agric*, *35*, 532–538.

Rauf, A., Imran, M., Abu-Izneid, T., Patel, S., Pan, X., Naz, S., Silva, A. S., Saeed, F.,

& Suleria, H. A. R. (2019). Proanthocyanidins: A comprehensive review. *Biomedicine & Pharmacotherapy*, *116*, 108999. https://doi.org/10.1016/j.biopha.2019.108999.

Reddy, P. P., & Reddy, P. P. (2016). High-Yielding and Adapted Varieties. *Sustainable Intensification of Crop Production*, 129–142.

Sáez-Plaza, P., Navas, M. J., Wybraniec, S., Michałowski, T., & Asuero, A. G. (2013). An overview of the Kjeldahl method of nitrogen determination. Part II. Sample preparation, working scale, instrumental finish, and quality control. *Critical Reviews in Analytical Chemistry*, *43*(4), 224–272. https://doi.org/10.1080/10408347.2012.751787.

Sambo, B. E. (2014). Endangered, neglected, indigenous resilient crops: A potential against climate change impact for sustainable crop productivity and food security. *IOSR Journal of Agriculture and Veterinary Science*, *7*(2), 34–41.

Shegro, A., Van Rensburg, W. S. J., & Adebola, P. O. (2013). Assessment of genetic variability in Bambara groundnut (*Vigna subterrenea* L. Verdc.) using morphological quantitative traits. *Academia Journal of Agricultural Research*, *1*(3), 45–51.

Shinda, C. A., Nthakanio, P. N., Gitari, J. N., Runo, S., Mukono, S., & Maina, S. (2022). Nutrient content of sorghum hybrid lines between Gadam and hard coat tannin sorghum cultivars. *Food Science & Nutrition*. https://doi.org/10.1002/fsn3.2830.

Sowndhararajan, K., Siddhuraju, P., & Manian, S. (2011). Antioxidant and free radical scavenging capacity of the underutilized legume, *Vigna vexillata* (L.) A. Rich. *Journal of Food Composition and Analysis*, *24*(2), 160–165.

Tan, X. L., Azam-Ali, S., Goh, E. Von, Mustafa, M., Chai, H. H., Ho, W. K., Mayes, S., Mabhaudhi, T., Azam-Ali, S., & Massawe, F. (2020). Bambara groundnut : An underutilized leguminous crop for global food security and nutrition. *Frontiers in Nutrition*, 276. https://doi.org/10.3389/fnut.2020.601496.

Temegne, N. T. D., Youmbi, E., NtsombC, Gouertoumob, W. F., Wakem, G. A., & Nkou, Ntsomboh-Ntsefong, G. (2018). Origin and Ecology of Bambara groundnut (*Vigna subterranea* (L.) Verdc.): A Review. *Journal of Ecology & Natural Resources*, *2*, 1–10.

Tripathi, A., Mishra, D. K., & Shukla, J. K. (2015). Genetic diversity and trait association between growth, yield and seed component of *Jatropha curcas* (L.) source collection from Indian sub-continent. *Journal of Plant Breeding and Crop Science*, *7*(5), 143–157.

Unigwe, A. E., Gerrano, A. S., Adebola, P., Pillay, M., & Monrovia, L. (2016). Morphological variation in selected accessions of Bambara groundnut (*Vigna subterranea* L. Verdc) in South Africa. *Journal of Agricultural Science*, *8*(11), 69–80.

Unigwe, A. E., Doria, E., Adebola, P., Gerrano, A. S., & Pillay, M. (2018). Anti-nutrient analysis of 30 Bambara groundnut (*Vigna subterranea*) accessions in South Africa. *Journal of Crop Improvement*, *32*(2), 208-224.

Vadivel, V., & Janardhanan, K. (2000). Nutritional and anti-nutritional composition of velvet bean: An under-utilized food legume in South India. *International Journal of Food Sciences and Nutrition*, *51*(4), 279–287.

https://doi.org/10.1080/09637480050077167.

Valombola, J. S., Akundabweni, L. M., Awala, S. K., & Hove, K. (2019). Agronomic and morphological diversity of Bambara groundnut (*Vigna subterranea* (L.) Verdc.) accessions in North-Central Namibia. *Wijas*, *1*(February), 88–99.

Vurayai, R., Emongor, V., & Moseki, B. (2011). Effect of water stress imposed at different growth and development stages on morphological traits and yield of Bambara groundnuts (*Vigna subterranea* L. Verdc). *American Journal of Plant Physiology*, *6*(1), 17–27.

Wabali, V. C., Giami, S. Y., Kiin-Kabari, D. B., & Akusu, O. M. (2020). Physiochemical, anti-nutrient and in-vitro protein digestibility of biscuits produced from wheat, african walnut and moringa seed flour blends. *Asian Food Sci. J*, 17–26. https://doi.org/10.9734/AFSJ/2020/v14i130120.

Wangithi, C. M., Muriithi, B. W., & Belmin, R. (2021). Adoption and dis-adoption of sustainable agriculture: a case of farmers' innovations and integrated fruit fly management in Kenya. *Agriculture*, *11*(4), 338.

Wild, Anna-Sophia (2022) Women and African Leafy Vegetables (ALVs): Cultivation and the informal seed system in Vihiga County, Kenya. Submitted in the framework of the Master program Organic Agricultural Systems and Agroecology (AgrEco-Organic), Vienna, April 2022. 71 p.

Xu, B. J., & Chang, S. K. C. (2007). A comparative study on phenolic profiles and antioxidant activities of legumes as affected by extraction solvents. *Journal of Food Science*, *72*(2), S159–S166. https://doi.org/10.1111/j.1750-3841.2006.00260.x.

Xu, M., Luan, Y., Zhang, Z., & Jiang, S. (2021). Dietary pattern changes over Africa and its implication for land requirements for food. *Mitigation and Adaptation Strategies for Global Change*, *26*(3), 13.

Yao, D. N., Kouassi, K. N., Erba, D., Scazzina, F., Pellegrini, N., & Casiraghi, M. C. (2015). Nutritive evaluation of the Bambara groundnut Ci12 landrace [Vigna subterranea (L.) Verdc.(Fabaceae)] produced in Côte d'Ivoire. *International Journal of Molecular Sciences*, *16*(9), 21428–21441. https://doi.org/10.3390/ijms160921428.

Zhang, X., Ding, W., Xue, D., Li, X., Zhou, Y., Shen, J., Feng, J., Guo, N., Qiu, L., & Xing, H. (2021). Genome-wide association studies of plant architecture-related traits and 100-seed weight in soybean landraces. *BMC Genomic Data*, *22*, 1–14.

Zondi, L. Z. (2012). *Responses of Bambara groundnut (Vigna Subterannea L. Verdc) landraces to field and controlled environment conditions of water stress* (PhD. Dissertation) University of KwaZulu-Natal.

APPENDICES

Appendix 1: Descriptors for Bambara groundnuts

The traits was characterized according to agro-morphological descriptors for Bambara groundnut (IPGRI, BAMNET, IITA, 2000) with modifications.

S/No	Descriptor	Descriptor State
1.	Stem hairiness	Recorded after harvest 0 Absent 3 Sparse 7 Dense
2.	Terminal leaflet shape	1 Round 2 Oval 3 Lanceolate 4 Elliptic 99 Other
3.	Pod shape	1 Without point 2 Ovate 3 Crescent 4 Bilobed 99 Other
4.	Pod color	1 Yellowish-brown 2 Brown 3 Reddish-brown 4 Purple 5 Black 99 Other
5.	Pod texture	1 Smooth 2 Slightly grooved 3 Much grooved 4 Much folded
6.	Seed shape	1 Round 2 Oval 99 Other
7.	Seed color	Determined by taking into consideration different testa colors 1 Cream 2 Dark red 3 Light red 4 Dark brown 5 Dark purple 6 Black 7 Reddish brown
8.	Number of days to first flowering	Number of days from sowing to flowering
9.	Number of days to 50% flowering	Number of days from sowing to 50% flowering
10.	Maturity period	The period from sowing and harvesting

11.	Plant height	Plant height measured from ground level to the tip of the highest point. Recorded 10 weeks after planting
12.	Number of tillers per plant	Number of tillers counted per plant
13.	Number of pods per plant	The number of pods counted per selected plants
14.	Seed length [mm]	Recorded within two months after harvest (average length of 10 seeds)
15.	Seed width (mm)	Recorded within two months after harvest (average length of 10 seeds)
16.	Weight of 100 Seeds (W100S)	Measured in weighing balance after counting
17.	Number of seeds per pods	Average number of 10 pods recorded within two months after harvest
18.	Yield	Determined by obtaining the weight of dried seed (at 12% moisture content)

Appendix 2: Determination of moisture content (Olayinka & Etejere, 2018)
Procedure

1. The lid and empty dish were placed in the drying oven at 105℃ for 3 hours until constant weight was achieved. After cooling in the desiccator for approximately 30 minutes, the empty dish and lid were weighed (**W1**).
2. The sample was precisely weighed at 3g into a pre-weighed drying container (**W2**).
3. The sample-filled dish was heated for three hours at 105 °C.
4. The dish containing the sample was placed in the desiccator to cool for 30 minutes before having its weight taken (**W3**).
5. Calculation

$$Moisture\ content\ \left(\frac{g}{100g}\right) = \frac{W2 - W3}{W2 - W1} x\ 100$$

Where: W1 = weight (g) of an empty dish with a lid
W2 = weight of dish containing the sample before drying (g)
W2 - W1 = sample weight (g)
W3 = final weight of the dish containing the sample after drying (g)
W2 – W3 = weight loss (g)

Appendix 3: Determination of ash (Olayinka & Etejere, 2018)
Procedure

1. Ashing dishes were heated to a temperature of 550°C for one hour in a muffle furnace, cooled to room temperature in a desiccator, and then precisely weighed.
2. For one hour, clean, clearly marked porcelain crucibles were heated to 105°C in the oven. They were cooled in a desiccator and weight noted.
3. 1-2g of grinded sample were weighed accurately into ashing crucibles.
4. Sample in the porcelain pan was heated on a low flame of a burner till the smoke/fumes ceased to appear.
5. Samples were incinerated for 3 hours while opening the lid at about 550℃ to 600℃ in a furnace.

6. The muffle furnace was switched off and the crucibles were removed using tongs when the temperature had dropped to at least 250℃ in the furnace.
7. The crucibles were transferred to the desiccator containing desiccant and weight taken quickly after removing from desiccator.
8. Ash content was calculated using the formula below.

$$\% \text{ ash} = \frac{\text{Weight after ashing - tare weight of crucible}}{\text{Original sample weight}} \text{ x } 100$$

Appendix 4: Determination of crude protein (Olayinka & Etejere, 2018*)*
Procedure

1. Samples weighing 1 g were placed in 250 ml digestion tubes.
2. Two Kjeldahl catalyst tablets were added to digestion tube and 1 glass bead was added to stop the solution from bumping.
3. To the digestion tubes, 12 mL of concentrated sulfuric acid was added.
4. For one hour, the digestion tube was heated to 420°C in the digestor. The mixture was quickly boiled until the solution was clear or blue green and free of carbon or until complete oxidation, after being initially digested at a low temperature to prevent frothing.
5. The digester's rack and exhaust manifold were taken out and allowed to cool to room temperature in a fume hood.
6. Tubes were transferred separately to the distillation unit after the exhaust manifold was removed.
7. After adding 100 mL of distilled water, 50 mL of sodium hydroxide at 40%, and 30 mL of boric acid to the digests, distillation was carried out.
8. In an Erlenmeyer flask with a 10 ml indicator, condensed liquid was collected.
9. Standardised 0.1 N hydrochloric acid was used to titrate the distillate until the pink color started to appear.
10. Calculation of Nitrogen percentage

    $\% N = [1.4007 \text{ x } (V_a - V_b) \text{ x } N] / W$

    Given that:

    V_a: Volume of acid used for sample titration

    V_b: Volume of acid used for the blank

    N: Normality of acid

    W: Sample weight in grams

    1.4007: Conversion factor milliequivalent weight of nitrogen and N percent

11. Percent crude protein calculation: CP = N x F, where F = 6.25.

Appendix 5: Determination of crude fat (Ether extract method) (Olayinka & Etejere, 2018)
Procedure

1. Extraction beaker was dried for 20 minutes at 105°C, cool in a desiccator and weight of the beaker was noted.
2. Extraction thimble was placed into thimble holder in the beaker and tared.
3. 2g of sample were placed into the thimble and plugged with fat free cotton wool.
4. Petroleum ether of 100ml was added into the extraction beaker then placed on Soxtherm. Then samples were covered with cotton wool.

5. Soxtherm was turned on for extraction to start. The extraction parameters were set as follows; temperature of hot plate at 150°C, hot extraction period 30min, rinsing time 1hr 20min and finally the evaporation time 10 min.
6. After the extraction process was completed, extraction beakers were removed and dried for 30 minutes at 105°C in a drying oven to remove any remaining moisture or solvent.
7. Subsequently, final weights were taken after extraction beakers had cooled completely to room temperature in a desiccator.
8. **Calculations**

$$\% \text{ of fat in sample } = \frac{(\text{Weight of the beaker } + \text{ extract}) - Beaker}{\text{Weight of sample}} X100$$

Appendix 6: Zinc determination

The procedures outlined by FSSAI (2015) were used to determine the concentrations of zinc and iron. To prepare series of zinc standards from a stock solution, 1 g of zinc sulphate was dissolved in 7 ml of concentrated HNO_3 and 14 ml of water in a volumetric flask of 1 L and the solution was then diluted with water to volume. 10 g of each sample were weighed into a clean crucible and burnt at 550℃ in a furnace for 3 hours. 5 ml of concentrated HNO_3 was added and heated in a hot plate till sample ash was dissolved. Another 5 ml of concentrated HNO_3 and 40 ml of distilled water was added and then heated for 10 minutes. The solution was then transferred to the 100 ml volumetric flask and filled up to the mark with distilled water. Atomic Absorption Spectrometer (AAS) - PG - 990 was used to determine zinc. Wavelength used was 213 nm. The absorbance of sample solutions and blank were then noted. The standard curve was created using the readings of the standard concentrations versus absorbance. Concentrations of sample solutions were then determined.

Appendix 7: Determination of iron (Nerdy, 2018)

To determine iron, iron nitrate was used to prepare standard solutions. 0.001 M of iron nitrate was used to prepare different concentrations of 20 ml, 15 ml, 10 ml and 5 ml into different test tubes. Test tube 1 had 20 ml of HCl and no iron nitrate. To test tube 2, 15 ml of deionised water and 5 ml of iron nitrate were then added. To test tube 3, 10ml of iron nitrate and 10 ml of deionised water were then added next. To test tube 4, 5ml of deionised water and 15 ml of iron nitrate were added. To test tube 5, 20 ml of iron nitrate was added. To each of the test tubes, 2.5 ml of 0.1M KCSN were added. A light with a wavelength of 458nm was employed in UV Spectrophotometer model ME 801. 1-2 g of each sample was burnt into ashes at 550℃ in a furnace for 3 hours. Ash

was dissolved in 10% HCl, heated, cooled, filtered and transferred to a 100 mL standard flask and filled up to the mark with deionized water. The standard solutions and sample solutions were placed in multiple cuvettes. The absorbance was then measured and noted. The standard curve was created using the readings of the standard concentrations versus absorbance. Concentrations of sample solutions were then determined.

Appendix 8*:* Determination of sodium and potassium

A method described by Nerdy, (2018) was used to determination sodium and potassium. Sodium chloride and potassium chloride were used to make stock solutions. Stock solutions were diluted in a 100 ml standard flask to prepare standard solutions. Ash was dissolved in 10% HCl, heated and cooled in a desiccator. The solution was then transferred to the 100 ml volumetric flask and filled up to the mark with distilled water. Standard solutions for potassium and sodium and sample solutions were aspirated separately in flame photometry model FP640 and results recorded. Standard curve of absorbance of samples and blank was used to determine the concentrations of potassium and sodium.

Appendix 9: Determination of tannin

To calculate tannin concentration, Wabali *et al*., (2020) technique was utilized. A 50 ml sample vial was filled with 200 mg of the sample. After adding 10 ml of 70% aqueous acetone, the mixture was completely covered. For two hours at 30°C, the bottles were shaken in an orbital shaker. Next, centrifugation and freezing were performed on the supernatant from each solution. 0.2 ml of each solution was pipetted into test tubes, followed by the addition of 0.8 ml of distilled water. After being diluted to 1 ml with distilled water, standard tannic acid solutions were created from a 0.5 mg/ml stock. The folin reagent and 2.5 ml of 20% Na_2CO_3 were applied to the sample and the standard equally. After the solutions had been vortexed, they were allowed to sit at room temperature for 40 minutes. UV Spectrophotometer model ME 801 was used to determine tannin at a wavelength of 291 nm. Absorbance measurements were made in comparison to a sample concentration of a standard reagent blank.

Appendix 10: Determination of flavonoid

The determination of flavonoid was done using the technique described by Olaleye *et al.* (2013). Five grams of the substance were repeatedly extracted using 100 ml of 80% aqueous methanol at room temperature. The whole solution was filtered through 125 ml of whatman filter paper. The filtrate was then placed in a crucible, dried out using an oven, and weighed to a set weight.

Appendix 11: Determination of saponin

The technique was Obadoni & Ochuko, (2001) approach. Into a conical flask, 5 g of the sample and 100 ml of 20% aqueous ethanol were added. The samples were subjected to heating for 4 hours while placed over a hot water bath with constant stirring and a temperature of 55°C. 200 ml of 20% ethanol were used to further extract the residue after filtering the mixture. At roughly 90°C, water bath was used to concentrate the combined extracts to 40ml. The concentrate was transferred in to a 250 ml separating funnel. 20 ml of diethyl ether was then added and shaken vigorously. The aqueous layer was recovered while the ether layer was discarded. A second round of purification was conducted to further remove any residual impurities. Afterward, 60 ml of n-butanol were added. Two separate washes with 10 ml of 5% aqueous sodium chloride were performed on the combined n-butanol extracts. The remaining solution was heated in a water bath after evaporation, and the sample was dried to a constant weight in an oven.

Appendix 12: Determination of alkaloid

The approach outlined by Olaleye *et al*. (2013) was followed in the determination of alkaloids. 5 g of the sample were weighed into a 250 ml beaker, along with 200 ml of 10% acetic acid in ethanol. After being covered, the mixture was left to stand for 4 hours. The extract was then filtered and concentrated to a quarter of the original volume on a water bath. Concentrated ammonium hydroxide was added drop wise to the extract until the precipitation had fully occurred. The solution was then allowed to settle. The precipitate was collected, washed with diluted ammonium hydroxide, and then filtered. After residue was dried, weight was recorded.

Appendix 13: ANOVA Tables

i. Kangaru site (combined seasons)

Analysis of variance (days to first flowering)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	16.133	16.133	8.604	**0.004**
Landrace	44.000	70.652	1.606	0.856	0.723
Rep	2.000	149.563	74.781	39.881	**<0.0001**
Season*Landrace	44.000	103.200	2.345	1.251	0.157

Analysis of variance (days to 50% flowering)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	94.815	94.815	41.199	**<0.0001**
Landrace	44.000	91.800	2.086	0.907	0.640
Rep	2.000	4.356	2.178	0.946	0.390
Season*Landrace	44.000	120.852	2.747	1.193	0.211

Analysis of variance (days to maturity)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	282.133	282.133	259.737	**<0.0001**
Landrace	44.000	123.163	2.799	2.577	**<0.0001**
Rep	2.000	9.985	4.993	4.596	**0.011**
Season*Landrace	44.000	1.533	0.035	0.032	1.000

Analysis of variance (seed length)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	77.838	77.838	890.807	**<0.0001**
Landrace	44.000	217.926	4.953	56.682	**<0.0001**
Rep	2.000	0.091	0.045	0.518	0.597
Season*Landrace	44.000	68.050	1.547	17.700	**<0.0001**

Analysis of variance (seed diameter)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	63.763	63.763	902.690	**<0.0001**
Landrace	44.000	85.401	1.941	27.478	**<0.0001**
Rep	2.000	0.071	0.035	0.500	0.607
Season*Landrace	44.000	46.885	1.066	15.085	**<0.0001**

Analysis of variance (plant height)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	62.314	62.314	16.924	**<0.0001**
Landrace	44.000	225.414	5.123	1.391	0.070
Rep	2.000	39.935	19.968	5.423	**0.005**
Season*Landrace	44.000	245.174	5.572	1.513	**0.032**

Analysis of variance (number of tillers)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	49.836	49.836	9.920	**0.002**
Landrace	44.000	387.736	8.812	1.754	**0.006**
Rep	2.000	34.481	17.241	3.432	**0.034**
Season*Landrace	44.000	137.473	3.124	0.622	0.968

Analysis of analysis (number of pods)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	4440.671	4440.671	142.870	**<0.0001**
Landrace	44.000	3691.313	83.893	2.699	**<0.0001**
Rep	2.000	569.885	284.942	9.167	**0.000**
Season*Landrace	44.000	1629.603	37.036	1.192	0.213

Analysis of variance (weight of 100 seeds)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	35595.807	35595.807	425.435	**<0.0001**
Landrace	44.000	9834.678	223.515	2.671	**<0.0001**
Rep	2.000	1110.293	555.147	6.635	**0.002**
Season*Landrace	44.000	8374.042	190.319	2.275	**<0.0001**

Analysis of variance (number of seeds)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	7341.416	7341.416	143.417	**<0.0001**
Landrace	44.000	23499.181	534.072	10.433	**<0.0001**
Rep	2.000	1050.340	525.170	10.259	**<0.0001**
Season*Landrace	44.000	3533.223	80.301	1.569	**0.022**

Analysis of variance (yield)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	80.251	80.251	334.678	**<0.0001**
Landrace	44.000	57.783	1.313	5.477	**<0.0001**
Rep	2.000	6.367	3.183	13.276	**<0.0001**
Season*Landrace	44.000	23.339	0.530	2.212	**0.000**

ii. Ishiara (combined seasons)

Analysis of variance (days to first flowering)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	28.033	28.033	10.491	**0.001**
Landrace	44.000	261.830	5.951	2.227	**0.000**
Rep	2.000	10.341	5.170	1.935	0.147
Season*Landrace	44.000	43.133	0.980	0.367	1.000

Analysis of variance (days to 50% flowering)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	149.633	149.633	32.025	**<0.0001**
Landrace	44.000	309.430	7.032	1.505	**0.034**
Rep	2.000	210.319	105.159	22.507	**<0.0001**
Season*Landrace	44.000	98.867	2.247	0.481	0.997

Analysis of variance (days to maturity)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	252.300	252.300	324.230	**<0.0001**
Landrace	44.000	82.533	1.876	2.411	**<0.0001**
Rep	2.000	4.822	2.411	3.099	**0.048**
Season*Landrace	44.000	6.533	0.148	0.191	1.000

Analysis of variance (seed length)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	27.742	27.742	2.720	0.101
Landrace	44.000	610.220	13.869	1.360	0.085
Rep	2.000	359.267	179.633	17.609	**<0.0001**
Season*Landrace	44.000	364.803	8.291	0.813	0.789

Analysis of variance (seed width)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	41.309	41.309	220.506	**<0.0001**
Landrace	44.000	72.985	1.659	8.854	**<0.0001**
Rep	2.000	0.600	0.300	1.601	0.205
Season*Landrace	44.000	39.447	0.897	4.786	**<0.0001**

Analysis of variance (plant height)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	2204.033	2204.033	300.148	**<0.0001**
Landrace	44.000	355.754	8.085	1.101	0.325
Rep	2.000	78.840	39.420	5.368	**0.005**
Season*Landrace	44.000	449.504	10.216	1.391	0.070

Analysis of variance (number of pods)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	13713.702	13713.702	311.902	**<0.0001**
Landrace	44.000	9047.970	205.636	4.677	**<0.0001**
Rep	2.000	1004.360	502.180	11.421	**<0.0001**
Season*Landrace	44.000	492.346	11.190	0.254	1.000

Analysis of variance (weight of 100 seeds)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	17119.096	17119.096	216.268	**<0.0001**
Landrace	44.000	17953.963	408.045	5.155	**<0.0001**
Rep	2.000	1579.660	789.830	9.978	**<0.0001**
Season*Landrace	44.000	9512.994	216.204	2.731	**<0.0001**

Analysis of variance (number of seeds)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	23236.566	23236.566	290.981	**<0.0001**
Landrace	44.000	38287.417	870.169	10.897	**<0.0001**
Rep	2.000	1547.201	773.600	9.687	**0.000**
Season*Landrace	44.000	4498.705	102.243	1.280	0.134

Analysis of variance (number of tillers)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	61.404	61.404	5.354	**0.022**
Landrace	44.000	748.350	17.008	1.483	**0.039**
Rep	2.000	148.553	74.277	6.476	**0.002**
Season*Landrace	44.000	367.094	8.343	0.727	0.893

Analysis of variance (yield)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	109.138	109.138	381.860	**<0.0001**
Landrace	44.000	92.763	2.108	7.377	**<0.0001**
Rep	2.000	7.127	3.563	12.467	**<0.0001**
Season*Landrace	44.000	21.763	0.495	1.731	**0.007**

iii. Kiamuringa (combined seasons)

Analysis of variance (days to first flowering)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	171.204	171.204	72.523	**<0.0001**
Landrace	44.000	89.467	2.033	0.861	0.715
Rep	2.000	156.467	78.233	33.140	**<0.0001**
Season*Landrace	44.000	133.630	3.037	1.287	0.129

Analysis of variance (days to 50% flowering)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	10.404	10.404	4.409	**0.037**
Landrace	44.000	97.274	2.211	0.937	0.588
Rep	2.000	5.363	2.681	1.137	0.323
Season*Landrace	44.000	165.096	3.752	1.590	**0.019**

Analysis of variance (days to maturity)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	270.000	270.000	277.887	**<0.0001**
Landrace	44.000	123.763	2.813	2.895	**<0.0001**
Rep	2.000	5.719	2.859	2.943	0.055
Season*Landrace	44.000	0.000	0.000	0.000	1.000

Analysis of variance (plant height)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	2404.806	2404.806	281.699	**<0.0001**
Landrace	44.000	300.474	6.829	0.800	0.807
Rep	2.000	668.755	334.378	39.169	**<0.0001**
Season*Landrace	44.000	329.145	7.481	0.876	0.691

Analysis of variance (number of tillers)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	31.260	31.260	3.433	0.066
Landrace	44.000	539.415	12.259	1.346	0.092
Rep	2.000	11.911	5.956	0.654	0.521
Season*Landrace	44.000	176.005	4.000	0.439	0.999

Analysis of variance (number of pods)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	16826.693	16826.693	486.842	**<0.0001**
Landrace	44.000	4918.240	111.778	3.234	**<0.0001**
Rep	2.000	661.432	330.716	9.569	**0.000**
Season*Landrace	44.000	359.176	8.163	0.236	1.000

Analysis of variance (seed length)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	155.087	155.087	488.651	**<0.0001**
Landrace	44.000	189.451	4.306	13.566	**<0.0001**
Rep	2.000	6.185	3.092	9.744	**<0.0001**
Season*Landrace	44.000	37.799	0.859	2.707	**<0.0001**

Analysis of variance (seed diameter)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	106.798	106.798	750.380	**<0.0001**
Landrace	44.000	53.480	1.215	8.540	**<0.0001**
Rep	2.000	2.866	1.433	10.069	**<0.0001**
Season*Landrace	44.000	37.152	0.844	5.933	**<0.0001**

Analysis of variance (weight of 100 seeds)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	79398.327	79398.327	694.545	**<0.0001**
Landrace	44.000	16904.115	384.184	3.361	**<0.0001**
Rep	2.000	8474.765	4237.382	37.067	**<0.0001**
Season*Landrace	44.000	16032.457	364.374	3.187	**<0.0001**

Analysis of variance (number of seeds)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	24134.360	24134.360	372.164	**<0.0001**
Landrace	44.000	37293.139	847.571	13.070	**<0.0001**
Rep	2.000	1441.205	720.602	11.112	**<0.0001**
Season*Landrace	44.000	5850.491	132.966	2.050	**0.001**

Analysis of variance (yield)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Season	1.000	278.892	278.892	745.916	**<0.0001**
Landrace	44.000	173.169	3.936	10.526	**<0.0001**
Rep	2.000	10.712	5.356	14.325	**<0.0001**
Season*Landrace	44.000	105.471	2.397	6.411	**<0.0001**

iv. Combined sites (combined seasons)

Analysis of variance (days to first flowering)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Site	2.000	95.341	47.670	18.784	**<0.0001**
Season	1.000	46.464	46.464	18.309	**<0.0001**
Landrace	44.000	149.400	3.395	1.338	0.077
Rep	2.000	180.652	90.326	35.592	**<0.0001**
Site*Season	2.000	168.906	84.453	33.278	**<0.0001**
Site*Landrace	88.000	272.548	3.097	1.220	0.098
Season*Landrace	44.000	36.758	0.835	0.329	1.000
Site*Season*Landrace	88.000	243.205	2.764	1.089	0.285

Analysis of variance (days to 50% flowering)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Site	2.000	268.496	134.248	39.627	**<0.0001**
Season	1.000	117.116	117.116	34.570	**<0.0001**
Landrace	44.000	252.444	5.737	1.694	**0.004**
Rep	2.000	58.689	29.344	8.662	**0.000**
Site*Season	2.000	137.736	68.868	20.328	**<0.0001**
Site*Landrace	88.000	246.059	2.796	0.825	0.867
Season*Landrace	44.000	142.217	3.232	0.954	0.559
Site*Season*Landrace	88.000	242.598	2.757	0.814	0.884

Analysis of variance (days to maturity)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Site	2.000	438.807	219.404	230.589	**<0.0001**
Season	1.000	804.011	804.011	844.999	**<0.0001**
Landrace	44.000	167.267	3.802	3.995	**<0.0001**
Rep	2.000	13.430	6.715	7.057	**0.001**
Site*Season	2.000	0.422	0.211	0.222	0.801
Site*Landrace	88.000	162.193	1.843	1.937	**<0.0001**
Season*Landrace	44.000	2.822	0.064	0.067	1.000
Site*Season*Landrace	88.000	5.244	0.060	0.063	1.000

Analysis of variance (plant height)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Site	2.000	3862.170	1931.085	270.993	**<0.0001**
Season	1.000	2586.736	2586.736	363.002	**<0.0001**
Landrace	44.000	349.426	7.941	1.114	0.288
Rep	2.000	435.788	217.894	30.578	**<0.0001**
Site*Season	2.000	2084.416	1042.208	146.255	**<0.0001**
Site*Landrace	88.000	532.216	6.048	0.849	0.829
Season*Landrace	44.000	438.768	9.972	1.399	**0.050**
Site*Season*Landrace	88.000	585.055	6.648	0.933	0.649

Analysis of variance (number of tillers)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Site	2.000	210.437	105.219	12.180	**<0.0001**
Season	1.000	139.900	139.900	16.195	**<0.0001**
Landrace	44.000	1126.735	25.608	2.964	**<0.0001**
Rep	2.000	104.269	52.135	6.035	**0.003**
Site*Season	2.000	2.600	1.300	0.150	0.860
Site*Landrace	88.000	548.766	6.236	0.722	0.970
Season*Landrace	44.000	434.379	9.872	1.143	0.250
Site*Season*Landrace	88.000	246.193	2.798	0.324	1.000

Analysis of variance (number of pods)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Site	2.000	3809.099	1904.549	51.902	**<0.0001**
Season	1.000	32752.729	32752.729	892.558	**<0.0001**
Landrace	44.000	9274.376	210.781	5.744	**<0.0001**
Rep	2.000	2004.660	1002.330	27.315	**<0.0001**
Site*Season	2.000	2228.337	1114.168	30.363	**<0.0001**
Site*Landrace	88.000	8383.147	95.263	2.596	**<0.0001**
Season*Landrace	44.000	753.381	17.122	0.467	0.999
Site*Season*Landrace	88.000	1727.744	19.633	0.535	1.000

Analysis of variance (seed length)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Site	2.000	136.285	68.142	17.339	**<0.0001**
Season	1.000	85.428	85.428	21.737	**<0.0001**
Landrace	44.000	663.089	15.070	3.835	**<0.0001**
Rep	2.000	139.015	69.508	17.686	**<0.0001**
Site*Season	2.000	175.239	87.619	22.295	**<0.0001**
Site*Landrace	88.000	354.508	4.029	1.025	0.424
Season*Landrace	44.000	177.314	4.030	1.025	0.430
Site*Season*Landrace	88.000	293.338	3.333	0.848	0.830

Analysis of variance (seed width)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Site	2.000	1.386	0.693	5.012	**0.007**
Season	1.000	204.133	204.133	1476.357	**<0.0001**
Landrace	44.000	142.766	3.245	23.467	**<0.0001**
Rep	2.000	0.402	0.201	1.453	0.235
Site*Season	2.000	7.737	3.868	27.978	**<0.0001**
Site*Landrace	88.000	69.100	0.785	5.679	**<0.0001**
Season*Landrace	44.000	64.986	1.477	10.682	**<0.0001**
Site*Season*Landrace	88.000	58.499	0.665	4.808	**<0.0001**

Analysis of variance (weight of 100 seeds)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Site	2.000	6146.398	3073.199	27.637	**<0.0001**
Season	1.000	120514.776	120514.776	1083.760	**<0.0001**
Landrace	44.000	24613.513	559.398	5.031	**<0.0001**
Rep	2.000	670.279	335.139	3.014	**0.050**
Site*Season	2.000	11598.454	5799.227	52.151	**<0.0001**
Site*Landrace	88.000	20079.242	228.173	2.052	**<0.0001**
Season*Landrace	44.000	20578.405	467.691	4.206	**<0.0001**
Site*Season*Landrace	88.000	13341.088	151.603	1.363	**0.022**

Analysis of variance (number of seeds)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Site	2.000	5710.822	2855.411	43.289	**<0.0001**
Season	1.000	51606.184	51606.184	782.376	**<0.0001**
Landrace	44.000	85062.580	1933.240	29.309	**<0.0001**
Rep	2.000	3420.948	1710.474	25.932	**<0.0001**
Site*Season	2.000	3106.158	1553.079	23.545	**<0.0001**
Site*Landrace	88.000	14017.157	159.286	2.415	**<0.0001**
Season*Landrace	44.000	10567.341	240.167	3.641	**<0.0001**
Site*Season*Landrace	88.000	3315.077	37.671	0.571	0.999

Analysis of variance (yield)

Source	DF	Sum of squares	Mean squares	F	Pr > F
Site	2.000	21.630	10.815	32.480	**<0.0001**
Season	1.000	434.530	434.530	1305.018	**<0.0001**
Landrace	44.000	228.178	5.186	15.575	**<0.0001**
Rep	2.000	5.176	2.588	7.773	**0.000**
Site*Season	2.000	33.751	16.875	50.682	**<0.0001**
Site*Landrace	88.000	95.537	1.086	3.261	**<0.0001**
Season*Landrace	44.000	88.633	2.014	6.050	**<0.0001**
Site*Season*Landrace	88.000	61.941	0.704	2.114	**<0.0001**