UNIVERSITY OF EMBU

ELIZAPHAN MBOI OMBASA

MSc

2024

PARTICIPATORY EVALUATION OF SPACING AND INTERCROPPING ON PRODUCTIVITY OF BAMBARA GROUNDNUTS AND SORGHUM IN EMBU COUNTY, KENYA.

ELIZAPHAN MBOI OMBASA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN AGRICULTURAL EXTENSION OF THE UNIVERSITY OF EMBU

AUGUST, 2024

DECLARATION

This thesis is my original work and it has not been presented for a degree in any other University.

Signature……………………………………...   Date…………………………...

Elizaphan Mboi Ombasa
A512/1205/2018
Department of Agricultural Economics and Extension

This thesis has been submitted for examination with our approval as the University supervisors.

Signature……………………………………...   Date…………………………...

Dr. Phyllis W. Muturi, PhD
Department of Water and Agricultural Resource Management
University of Embu

Signature……………………………………...   Date…………………………...

Dr. Bernard M. Gichimu, PhD
Department of Water and Agricultural Resource Management
University of Embu

Signature……………………………………...   Date…………………………...

Dr. Hezron N. Isaboke, PhD
Department of Agricultural Economics and Extension
University of Embu

DEDICATION

This work is dedicated to my mother, Doris, wife Elizabeth, and our sons, Jayden and Louis.

ACKNOWLEDGEMENT

I wish to express my gratitude to my supervisors: Dr. Phyllis Muturi, Dr. Bernard Gichimu and Dr. Hezron Isaboke for always being available for me and offering guidance during proposal writing, execution of the research project, manuscripts writing to the final thesis write-up. I wish to appreciate the Vice-Chancellor, University of Embu for the research grant 2019/2020 that funded this study. I also acknowledge Kenya Agricultural & Livestock Research Organization (National Agricultural Research Laboratories) Nairobi for soil analysis. I appreciate the farmers who hosted the on-farm experiment as well as those farmers who participated in the study in the three sites. Special thanks to my colleagues: Peter Anunda, Collins Musafiri, Stephen Onkoba and Kennedy Musyoka for the support I received from you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS AND ACRONYMS

ESM	Equivalent Soil Mass
LAI	Leaf Area Index
LER	Land Equivalent Ratio
LM	Lower Midland
SOC	Soil Organic Carbon
SR	Short Rains
LR	Long Rains
Tg	Tera-grams

MAIN ABSTRACT

Bambara groundnut (*Vigna subterranea* L. Verdc) is underutilised in Kenya, and little is known on its best agronomic practices in various agroecological zones. The objective of this study was to determine the influence of spacing and intercropping on the productivity of Bambara groundnut and sorghum in Embu County using a farmer-participatory approach. Two separate experiments were conducted in three sites in Mbeere North, Mbeere South and Embu West, sub-counties of Embu County. The experimental design was a randomized complete block design replicated thrice in each site. The experiments were conducted in two seasons: during the short rains (October – December 2019) and long rains (March-May 2020). The first experiment was to determine the optimum spacing of Bambara groundnut, where the main plot treatments were three landraces, namely BG 001, BG 003 and BG 005. The treatments were three population densities: S1 = 50 cm x 20 cm, S2 = 50 cm x 30 cm, S3 = 50 cm x 40 cm. Data was taken on Bambara plant spread, leaf area index, number of branches per plant, the weight of grains per plant, number of pods per plant, length of pods, number of seeds per pod, 100 grain mass, and total dry weight land equivalent ratio. The second experiment assessed the effect of intercropping of Bambara groundnuts with sorghum on sorghum productivity. The treatments included T1 - monocrop sorghum spaced at 60 cm x 20 cm, T2 - monocrop Bambara groundnut spaced at 50 cm x 20 cm, T3 - sorghum with one row of Bambara groundnut intercrop 120 cm x 15 cm with legume residues removed after harvest and T4 - Sorghum with one row of Bambara groundnut intercrop 120 cm x 15 cm with legume residues incorporated into the soil. Local farmers were involved in data collection through organized farmers' field schools to enable them to make informed adoption decisions. The participants were sampled using a multistage spatially stratified random sampling design. Sorghum data was taken: panicle length, weight, 100 grain mass and total yield per plant. The third study assessed the smallholder farmers' willingness to adopt the best agronomic practices of Bambara groundnut; the study involved 384 small-scale farmers sampled from the farmers' field school participants from the three sites. The respondents were interviewed using a structured questionnaire. The agronomic data from the first and second experiments was subjected to a three-way analysis of variance, and treatment means were separated using Tukey's Honestly Significant Difference at 95% confidence level. The socioeconomic data was subjected to descriptive statistics, including means, frequencies and percentages, using SPSS. The study concluded that spacing of 50 cm x 20 cm was optimum with the highest yield of 6.02 ton ha^{-1} among the three landraces of Bambara groundnut tested with landrace BG 001 recording the highest total grain yields of 4.49 ton ha^{-1}. Intercropping sorghum with Bambara groundnut residues removed and intercropping sorghum with Bambara groundnut residues incorporated into the soil recorded land equivalent ratio greater than 1, indicating yield advantage over sorghum and Bambara groundnut monocrops which recorded land equivalent ratio less than 1. The proportion of farmers who showed willingness to adopt the best agronomic practices of Bambara groundnut production was 60.94%. The study recommended growing landrace BG 001 of Bambara groundnut at a spacing of 50 cm x 20 cm in the study area and other areas with similar agroecology. The study recommends intercropping sorghum between two rows of Bambara groundnuts since it resulted in higher sorghum yields with 3.74 mg ha^{-1}.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Attempts are underway to introduce Bambara groundnut (*Vigna subterranea* L. Verdc) to other areas beyond Africa with comparable environmental circumstances (Njeri et al., 2023). Its potential as a worldwide crop is being investigated, particularly in Asia and Latin America, by looking into how adaptable it is to various soil types and climates (Barton & Li, 2022). Bambara groundnut landraces are an African native legume that may flourish on less fertile soils and resistant to heat and water scarcity (Olanrewaju et al., 2022). The crop is indigenous to Northern Cameroon and Northeastern Nigeria (Akinyosoye et al., 2023). Bambara groundnut ranks third in importance among legumes in Sub-Saharan Africa (SSA), behind cowpeas and groundnuts (Maphosa et al., 2022). The twelve-monthly world production is 330,000 metric tonnes, of which 45 to 50% is planted in West Africa (Majola et al., 2021). The biggest producer of the legume is Nigeria, which produces 100,000-168,700 metric tonnes, covering 15,350 hectares of land (Onuche et al., 2020). In Kenya, the crop is grown in Western, Nyanza, and coastal areas (Chelangat et al., 2023) on small scale for subsistence use.

Bambara groundnut is grown to give pods for cooking or ground into flour for stiffing porridge (Sadiq et al., 2022). The crop is highly nutritive, with 19% protein, 10% dietary fibre, 6.5% oil content and 63% carbohydrates (Hlanga, 2021). Besides, it has minerals such as calcium, iron, potassium, and sodium (Musah et al., 2021). Bambara groundnut is rich in protein content and helps improve people's nutrition, while its leaves and stalks are fed to animals (Ogbuagu et al., 2023). Like other leguminous plants, Bambara groundnut fixes free nitrogen from the atmosphere through a symbiotic relationship with rhizobium bacteria (Nweke & Anene, 2019). This improves soil fertility and makes it suitable for use as an intercrop with other crop varieties like maize, resulting in a higher output (Tan et al., 2020).

Although Bambara groundnut is underproduced in numerous sub-Saharan African areas, including some parts of Kenya, its agronomic package has not been fully developed. Farmers reportedly use varied agronomic practices for the crop (Egbe, 2013). For example, in Nigeria, the common spacing is 60 cm by 30 cm, resulting in low yields of 600 Kg ha-1, while in Tanzania, it is 30 cm by 30 cm, yielding 1000 Kg ha^{-1} (Egbe, 2013). The effect of intercropping the crop with other drought-resistant plants, such as sorghum, on conserving the soil and water is scanty. The current study addressed this gap and provided some recommendations for adoption in growing Bambara groundnut in dry areas where its production is less popular (Boulay et al., 2021). It has a great potential to improve sustenance and dietary consistency in dry regions. However, it needs more promotion as a vegetable and food (Mbosso et al., 2020). The minimal uptake of improved farming technologies is associated with poor channels of communication used to create awareness among the farmers (Sennuga et al., 2020). The study engaged farmers through a participatory approach to promote Bambara groundnut growing in dry regions in Embu County. Although Bambara groundnuts have great potential, agronomic practices like spacing and intercropping techniques frequently restrict their adoption and productivity. There is a need to optimise Bambara groundnut agronomic practices to increase yield and income for smallholder farmers (Gonzalez et al., 2021; Akintoye et al., 2022).

1.2 Statement of the Problem

Frequent droughts and low soil fertility have led to declining agricultural productivity in semi-arid areas, especially in Embu County, Kenya. Drought-tolerant crops with low demand for fertilizers, such as Bambara groundnut, have not been well promoted in semi-arid areas. Despite its high agronomic potential and nutritive value, Bambara groundnut is not popular in most communities in Kenya except in Western, Nyanza, and Coastal regions. The farmers' willingness to adopt the crop in dry areas of Embu County, Kenya, has not been reported. In addition, there is scanty information regarding the spacing and intercropping requirements of this crop with dryland cereal crops such as sorghum. It was reported that farmers use varied spacing either in a pure stand or in intercropped systems in West Africa and other parts of SSA. Farmers' beliefs rather than experiments drive the decisions of spacing Bambara groundnuts. Thus, the study sought to develop the agronomic packages of spacing and intercropping and promote Bambara groundnuts in the dry areas of Embu County.

1.3 Justification

Sorghum and Bambara groundnuts are food crops with great potential to solve food insecurity cases in Kenya's semi-arid and dry regions due to their tolerance to water scarcity and ability to thrive in impoverished soils. Although other leguminous crops, such as common beans, cannot be cultivated in marginal soils, Bambara groundnuts can withstand high temperatures. The current research contributes to developing an agronomic package of Bambara groundnuts in semi-arid areas and identifying optimum spacing, which results in optimum yields of Bambara groundnuts and improves farmers' food security and income generation. Intercropping sorghum with Bambara groundnut results in high sorghum yields since Bambara is a legume and increases the incorporation of atmospheric nitrogen into the soil. Improved productivity of both Bambara groundnut and sorghum would improve food and nutritional security among the resource-poor farmers in the dry lands of Embu County, therefore ensuring the food security pillar of the “Big Four Agenda” of the government of Kenya (GoK, 2007). In addition, it would generate additional household income, thus improving the farmers’ livelihood as per the first Sustainable Development Goal (SDG 1) on poverty eradication (Le, 2015). Besides, the study contributes to attaining the Kenya Vision (2030), which emphasizes attaining ten per cent annual economic growth (Onyango, 2017).

1.4 Research Objectives

1.4.1 General Objective

To evaluate the spacing and intercropping options for enhanced Bambara groundnut and sorghum productivity in Embu County, Kenya.

1.4.2 Specific Objectives

1. To determine the optimum spacing for the production of selected Bambara groundnut landraces in semi-arid lands of Embu County, Kenya.
2. To evaluate the agronomic benefits of intercropping sorghum with Bambara groundnut in the semi-arid lands of Embu County, Kenya.
3. To assess the willingness of smallholder farmers to adopt the best agronomic practices of Bambara groundnut in semi-arid lands of Embu County, Kenya.

1.5 Research Questions

1. What is the optimum spacing for production of selected Bambara groundnut landraces in semi-arid lands of Embu County, Kenya?
2. What are the agronomic benefits of intercropping sorghum with Bambara groundnut in semi-arid lands of Embu County, Kenya?
3. What is the level of willingness of the farmers to adopt the best agronomic practices of Bambara groundnut in the semi-arid lands of Embu County, Kenya?

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of Bambara Groundnut

Bambara groundnut, also known as Bambara bean or Bambara nut, fits the family *Fabaceae*, tribe *Phaseoleae,* genus *Vigna* and species *Vigna subterranean L. Verdc* (Tsoata et al., 2017). It is a bushy plant with several running stems and short internodes (Al-Hamdi et al., 2924). Bambara groundnut is a geocarpic crop closely related to cowpea (Vigna unguiculata) (Feldman et al., 2019). However, its morphology is like that of groundnuts (Arachis hypogaea), while the seed nearly resembles that of chickpea (*Cicer arietinum*) (Feldman et al., 2019a). Besides being trifoliate, the leaves cluster together and arise from separated stems (Olanrewaju, 2022). The leaves are attached to erect petiole, which is thickened at the base, and their colour ranges from green to purple (Dlamini et al., 2021). The seeds of Bambara groundnuts are contained in a pod that forms underground (Mateva et al., 2023). The pods are 1 to 5 cm long, wrinkled and round, with one to two seeds inside (Xulu et al., 2024). They are indehiscent and reddish brown or yellow when mature, while the seeds are hard, smooth and round (Mensah, 2011). The colour of the seeds can be black, white or red speckled depending on the type of landrace (Chinedu & Nwinyi, 2012).

Bambara groundnut was first grown in dry areas of West Africa near River Niger, from where it spread in ancient times to Central Africa, South America and Asia (Hantgan, 2024). Nigeria is the leading producer of the legume (Gbenyi et al., 2016), followed by Niger, Ghana, Botswana, Zimbabwe, South Africa, Cote d'Ivoire, and Swaziland. It is also grown in Indonesia (Mayes et al., 2019). In Kenya, Bambara groundnut is principally planted by communities in the country's Western, Nyanza, and Coastal regions (Wasula et al., 2014). The bean is majorly grown by the Luhya community for subsistence use and is locally called "Mbande" (Oyugi et al., 2015). Landraces of numerous inbred lines chosen and cultivated over multiple seasons are the primary form of the legume grown (Zeven, 1998). The crop has excellent potential to yield (1.2 ton ha^{-1}) more in dry lands (Chai et al., 2016), but this potential remains underutilised (Chivenge et al., 2015).

Bambara groundnut is highly nutritious and is considered a whole meal. The seeds contain vitamins C, A and E (Oladimeji et al., 2024). In Senegal, the shoots and seeds of Bambara groundnut have been applied to heal abscesses and ulcers, epilepsy, cataracts and venereal diseases (Tshikukuvhe, 2017). In other countries like Cameroon, the crop has been used to treat bone decalcification, stomach pain, amoebic dysentery, sore throat and headaches (Temegne et al., 2018). Bambara groundnut is an antioxidant that reduces cancer risks (Diedericks & Jideani, 2015). The crop also stimulates milk production in breastfeeding mothers and helps digestion through laxative properties (Temegne et al., 2018). Bread can be made with Bambara groundnut flour (Nwosu, 2013). Bambara leaves contain phosphorus and are used as animal fodder (Séraphin et al., 2024).

In sub-Saharan Africa, smallholder farmers depend on amabambara groundnuts as a steady source of cash income (Chai et al., 2016). The crop is favored in areas with difficult agricultural conditions because of its resistance to drought and low soil fertility (Munyua et al., 2021). Bambara groundnut make a substantial contribution to food security in households. The legume promotes dietary diversity and fights malnutrition, particularly in regions where traditional crops might not be able to flourish (Dube et al., 2021). Trade in Bambara groundnut is growing both domestically and globally. Increased market accessibility and export potential for Bambara groundnuts, according to recent analyses, may help develop regional economies (Adegboyega & Ogundele, 2021). Bambara groundnuts give smallholder farmers in sub-Saharan Africa a vital source of revenue. The crop is resistant to drought and require little input, making it a dependable crop in agricultural instability (Molefe et al., 2020).

Germination and environmental factors affect the maturity phase. Landraces planted vary from 7 to 15 days to germinate and 110 to 150 days to mature (Ibrahim et al., 2024). During planting, In heavy soils, the depth of the seeds should be 2.5 to 3.0 cm with high moisture content or 5.0 to 6.5 cm deep in loose soils such as sandy soils (Mkandawire, 2007). Effa et al. (2016) noted that the density of planting of Bambara groundnut is less than 100,000 plants per hectare. Bambara groundnut is tolerant to low soil moisture content (Tsoata et al., 2017). The legume takes 64 to 66 days after planting under rain-fed conditions and 86 to 88 days after planting under irrigation to attain 50% flowering (Mabhaudhi et al., 2013). It takes about 30 to 40 days, on average, after pollination for Bambara groundnut pods and seeds to develop to maturity.

Different researchers have made contradictory statements about the moisture requirement of Bambara groundnut. Tsoata et al. (2015) reported that the crop requires yearly rainfall extending from 300 to 750 mm for optimum growth. Feldman et al. (2019b) stated that the Bambara groundnut requires a minimum of roughly 500 mm of annual precipitation and 1200 mm of optimal precipitation for optimum growth. The crop can tolerate heavy rainfall but not exceed 3000 mm, especially around the harvest period, as it might lead to a loss of yields (Adzawla et al., 2016). The optimum temperature range is from 19ºC to 30ºC (Chai et al., 2016). The crop does not have a coordinated seed systems (Feldman et al., 2019a). Plant spacing needs to be ideal to maximize Bambara groundnut output. Even though various spacing arrangements have been explored, there is disagreement on the ideal spacing to maximize growth and yield (Afolabi et al., 2022). Although some studies imply that closer spacing promotes pod production, others suggest that broader spacing may increase plant health and lessen resource competition (Mwangi et al., 2023).

2.2 Intercropping of Bambara Groundnut with Cereals

Bambara groundnut uses rhizobium bacteria to fix nitrogen from the atmosphere (Pule-Meulenberg, 2018). The crop fixes 33 to 46 Teragrams (Tg) of Nitrogen per year (Sambo, 2014). This phenomenon aids in increasing fertility in the soil status, and the crop has been used in crop rotation and intercropping programs, especially with cereals. It can yield 1.2 ton ha^{-1} in acidic and poor soils (Oyewole, 2018). Promoting Bambara groundnut is a climate change mitigation strategy as it reduces fossil fuel usage by providing the essential ingredients needed for biobased economies (Sambo, 2014). Bambara groundnut is resilient and adaptive to water stress, high temperatures, and declining precipitation (Tsoata et al., 2017).

One of the advantages of intercropping cereals and legumes is stabilized and improved yields (Moreira et al., 2024). The cereal grain protein also tends to increase in cereal-legume intercropping methods compared to mono-crop techniques (Jensen et al., 2007). Intercropping cereals and legumes smother weeds by acting as a cover crop, enhancing soil and water conservation, decreasing pests and disease incidences, and resistance to the lodging of crops (Naudin et al., 2010). Research by Njeru et al. (2013) specified that improved agricultural technologies like intercropping sorghum with soybean may result in soil moisture conservation and improved crop productivity. This corroborated earlier reports by Mugwe et al. (2009) that incorporating legumes in the farm can increase moisture conservation and crop yields in Eastern Kenya. In Burkina Faso and Botswana, Bambara groundnut is planted alongside sorghum, millet, and maize (Muleba et al., 1997). In Ghana, the nut is embedded in yam mounds to protect the mounds from erosion (Hillocks et al., 2012). Jensen et al. (2015) report that intercropping has a great latent for increasing crop yields with less harm to the environment than mono crops. The land area monocrops must yield an equivalent amount as an intercrop unit, known as the Land Equivalency Ratio (LER) (Yu, 2016). The land equivalent ratio (LER) assesses the yield advantage of intercrops. Intercropping sorghum and Bambara groundnut increase yield and land use efficiency. Intercropping systems may provide advantages, including improved soil health and insect management (Osei et al., 2022). Few studies have examined the synergy between Bambara groundnuts and sorghum on growth dynamics and overall productivity. Therefore, the empirical evidence supporting these benefits is sparse (Ali et al., 2023).

2.3 Adoption of Bambara Groundnuts by Farmers

Adoption refers to the process by which farmers start using new crop varieties or techniques to increase resilience and productivity. Studies reveal that awareness, perceived advantages, and socioeconomic circumstances are essential variables in the uptake of Bambara groundnut (Adebayo et al., 2022). Bambara groundnut potential to mitigate climate change's effects is becoming more widely acknowledged. Bambara groundnuts require less water than other legumes and can fix nitrogen (Moyo et al., 2021). Despite its promise, Bambara groundnut production is still underutilised in dryland areas, including Kenya's Embu County. There is inadequate information on the best farming techniques for Embu County's dryland environment. Studies on the socioeconomic effects of adopting bambara groundnuts in these regions are scarce. Closing these gaps may offer information on how to raise adoption rates and raise farmers' living standards in areas vulnerable to drought (Kimani et al., 2023).

Access to relevant information and credit facilities increased small-scale farmers' readiness to adopt legumes and maize tolerant to drought in South Africa (Makate et al., 2019). Farmers with a wide range of experience over the years and those who have attained an ordinary level of education are readily willing to uptake climate-smart techniques of the soil in Western Kenya (Mogaka et al., 2021). Land size is one of the factors that leads to low adoption of better technologies in agriculture (Ngetich et al., (2012). Smallholder farmers find the new agricultural techniques unattractive since they result in low yield and stalemate land. Large landholders are risk-takers since they can invest part of the land in trials (Amsalu & Graaff, 2006).

Researchers, extension officers, and other agents of change influence the uptake of advanced agricultural technology (Moser & Barrett, 2003). The delayed adoption tendency has been exacerbated by the target farmers and change agents having less contact. Tey et al. (2017) state that adopting better agricultural technologies is always higher where farmers associate closely with the change agent. Adopting optimal agronomic practices is lacking in Bambara groundnuts since the crop is uncommon, especially in the dry parts of Eastern Kenya (Wasula et al., 2014). Theoretically, farmers' desire to adopt the optimum agronomic methods for Bambara groundnut was significantly impacted by their socioeconomic status and involvement in agronomic evaluation. Establishing appropriate extension channels is pertinent to increasing the adoption of new technologies.

2.4 The Adoption of Innovation Theory

The current research was led by the “adoption of innovation theory” that was established by Carl Rogers (Sherry & Gibson, 2002). According to this theory, adoption is deciding to practice an innovation fully as the best way of action. As people adopt a new technology, product idea, or practice, diffusion occurs (Kaminski, 2012). Diffusion is a message passing that includes innovation, channels and adoption (Sahin, 2006). The critical components of adoption include communication channels and social systems (Rogers, 2003). Pathways through which information is transmitted from one point to another are known as the channel (Sahin, 2006). Communication occurs when partakers craft and pass the message to others

(Kaminski, 2012). A social system comprises several linked entities cooperating to resolve issues and achieve a shared goal (Rogers, 2003).

An individual engaged in the innovation-decision process is driven to eliminate doubt about the advantages and disadvantages of an invention by obtaining data and information-processing activities (Rogers, 2003). Sahin et al. (2006) describe the five steps in the adoption innovation process: knowledge, decision-making, persuasion, execution, and confirmation. Diffusion includes speaking with people personally (Rogers, 2003). The interpersonal channels of communication are pertinent in changing attitudes among people. These communication channels can be locality, for example, interpersonal channels, or cosmopolite, which are individuals outside the sources, e.g., mass media. At the informational level, the interpersonal routes are crucial in the innovation-decision process, whereas localite channels are more critical during persuasion (Sahin, 2006). Rogers (2003) gives attributes of individual perceptions that affect the speed of adoption, including the relation benefit of the invention, trial-ability, compatibility, convolution, and observability.

Adopting innovation is the best framework for examining the uptake of technologies in research institutions, farming and education studies (Raza et al., 2021). Rogers (2003) narrates that the innovation-diffusion process reduces uncertainty about various innovations. Innovations have attributes: comparative benefit, suitability, intricacy, feasibility, and observability. How farmers perceived these characteristics predicted the adoption rates. Rogers recorded a variation of 49-87% in the rate of innovation uptake, which was accounted for by the characteristics. Consequently, channels of communication, social systems and agents of change raise the prediction rates of innovations.

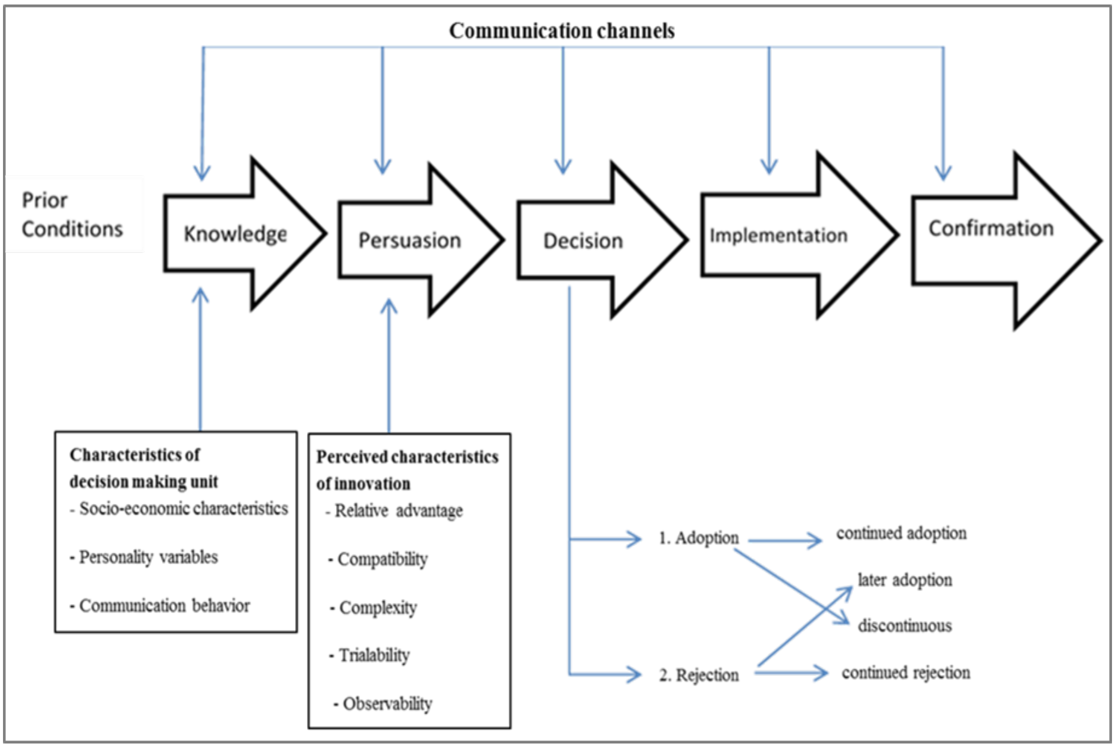

Figure 2.1: Innovation–decision theory chart adopted from Sahin *et al.* (2006).

2.5 Conceptual Framework

Different crop spacing affects the experiment's growing and yields of Bambara groundnuts. Intercropping Bambara groundnuts with sorghum affects crop productivity, moisture content, and soil fertility in the study. Farm characteristics and the farmers' level of awareness of Bambara groundnuts influence the farmers' willingness to adopt them (Figure 2.2).

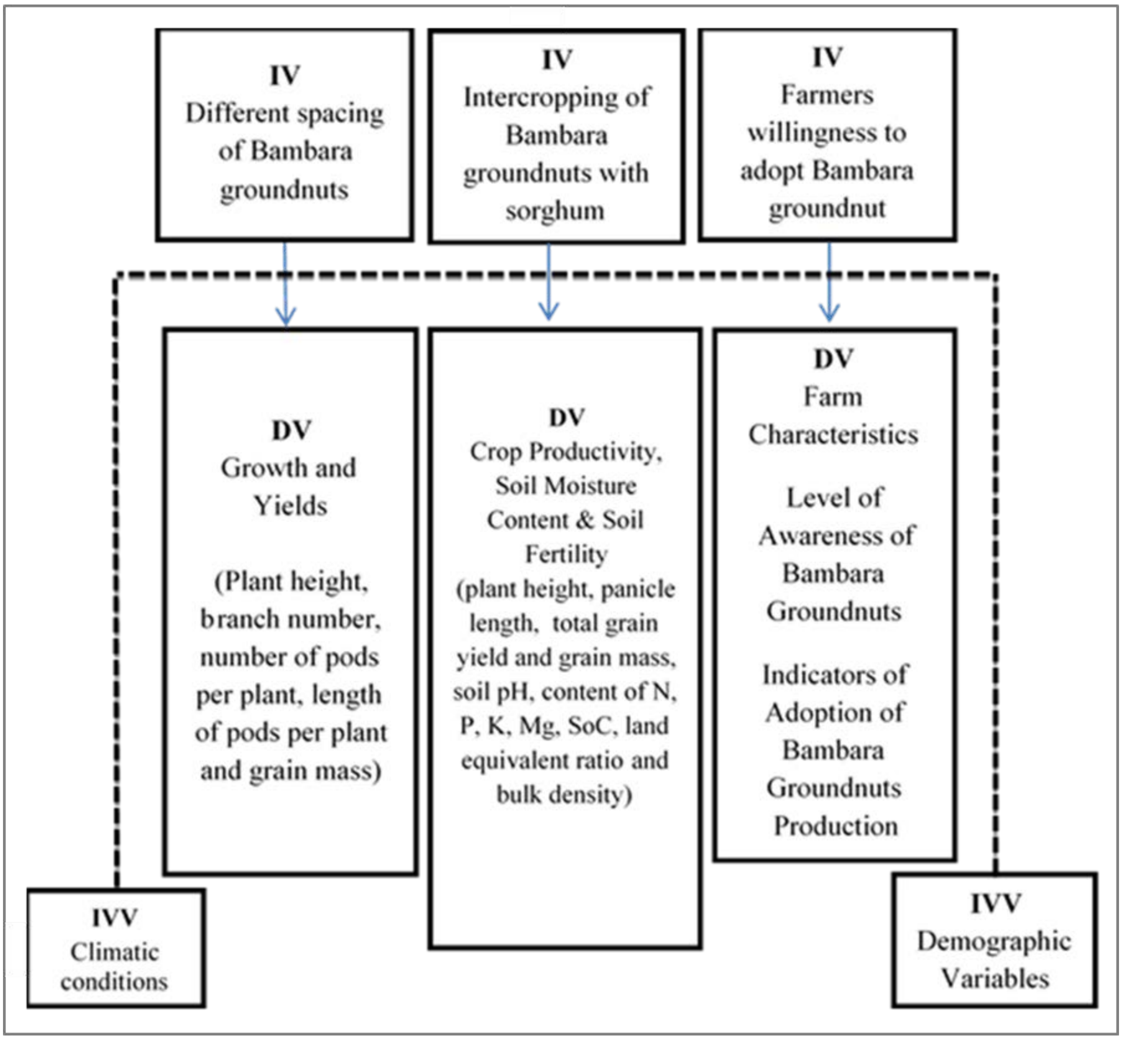

Figure 2.2: Conceptual Framework; DV is the Dependent Variable, IV is the Independent Variable, IVV is the Intervening Variable

CHAPTER THREE

DETERMINATION OF THE OPTIMUM SPACING FOR SELECTED BAMBARA GROUNDNUT LANDRACES IN SEMI-ARID LANDS OF EMBU COUNTY, KENYA

Abstract

There is scanty information on the spacing requirements of Bambara groundnuts and different farmers have been using different spacing. The objective of this investigation was to determine the optimum spacing for the production of selected Bambara groundnut genotypes in dry areas of Embu County, Kenya. The study was conducted in three selected sites in Embu County: Ishiara Ward in the Mbeere North sub-county, Kiamuringa Ward in the Mbeere South sub-county, and the University of Embu in the Embu West Sub-County. The experimental design was a randomized complete block design laid in a split plot with three replications. The main plot treatments were three population densities: S1 = 50 cm x 20 cm, S2 = 50 cm x 30 cm, S3 = 50 cm x 40 cm, while the sub-plots were three selected landraces: BG 001, BG 003, and BG 005. The local farmers were involved in data collection through organized farmers' field schools to enable them to make informed adoption decisions. Data was taken on the plant height, plant spread, leaf area index, number of branches per plant, weight of grains per plant, number of pods per plant, length of pods, number of seeds per pod, and total dry weight. Three way Analysis of variance was used to analyse agronomic data, and treatment means were separated using Student-Newman-Keuls at a 95% confidence level. Spacing 1 (50 cm x 20 cm) was optimal for producing Bambara groundnut, with landrace BG 001 being the best yield, with 6.02 tons $^{-1}$ in the study areas. The study recommended spacing 1 (50 cm x 20 cm) as the optimum for planting Bambara groundnut among the three landraces tested in this study area.

3.1 Introduction

Bambara groundnut (*Vigna subterranea* L. Verdc) originated in sub-Saharan Africa and is commonly cultivated for subsistence use (Bendu et al., 2023). The crop has drought-tolerant attributes and thrives in marginal soils, giving the legume a great potential to increase nutrition security in semi-arid areas (Asiwe, 2020). The crop can be used as green manure, improving soil fertility (Umeugokwe et al., 2021). Bambara groundnut, a leguminous plant, is essential in fixing free nitrogen via a mutualistic relationship with rhizobium bacteria (Khan et al., 2021). The crop, being rich in protein content, helps to improve nutrition for the people while the leaves and stalks are fed to animals (Hasan et al., 2018).

The crop is of great nutritional importance, ranging from proteins to carbohydrates and fats (Agu et al., 2020). Bambara groundnut yields vary considerably among the landraces, seasons and sites. Khan et al. (2021) recorded that Bambara groundnut can yield 0.7 to 2.0 tonnes/ha. Bambara groundnuts can yield pods up to 4.4 t ha^{-1} and seeds up to 3.4 t ha $^{-1}$ (Berchie, 2010). It is reported that farmers used varied spacing and growing of Bambara groundnuts. A report by Dunbar (1969) recorded that farmers from Bukoba, Tanzania, commonly use spacing 30 cm x 30 cm in growing Bambara groundnuts. Bendu et al. (2023) recommended 50 cm x 25 cm as the optimum spacing for inter-row growing bambara groundnuts in Sierra Leone. A study by Kouassi and Zoro (2010) reported that planting bambara groundnuts in a high density of 25 plants per square meter yielded the highest in Cote d’Ivoire. Bambara groundnuts are typically grown with specific row spacing to provide sufficient room for the plants to spread and develop (Dodd et al., 2023). In traditional farming systems, intra row spacing for Bambara groundnuts ranges from 60 cm to 90 cm (Mawiya, 2016). This spacing allows the plants to grow without being too crowded, facilitating optimal sunlight penetration, airflow, and nutrient absorption (Hussin et al., 2020). The common plant intra spacing for Bambara groundnuts falls between 10 cm and 20 cm (4-8 inches) apart (Garkebo et al., 2020). This spacing allows each plant to access sufficient sunlight, nutrients, and water, promoting healthy root development and minimising resource competition.

Bambara groundnut spacing can be adjusted based on specific farming practices, goals, and available resources (Sidibé et al., 2020). Wider spacing between Bambara groundnut plants enables them to grow without overshadowing or inhibiting the growth of the Bambara groundnuts. To determine the most suitable spacing for growing bambara groundnuts in a particular region, it is crucial to consider local environmental conditions and farming practices (Olanrewaju et al., 2021). These studies often consider soil type, rainfall patterns, and available resources. Optimum spacing contributes to healthier plant growth, efficient resource utilisation, and improved crop yields. The spacing requirements for Bambara groundnut can vary based on aspects such as soil richness, water obtainability, and the variety being cultivated. (Bonny et al., 2019).

Although Bambara groundnut has been under production in diverse parts of sub-Saharan Africa and some parts of Kenya, its agronomic package has not been fully developed. Farmers reportedly use varied agronomic practices for the crop (Egbe, 2013). For example, in Nigeria, the standard spacing is 60 cm by 30 cm, while in

Tanzania, it is 30 cm by 30 cm (Egbe, 2013). The current study was to addressed this gap by developing an agronomic package for Bambara groundnut in semi-arid areas.

3.2 Materials and Methods

3.2.1 Description of Study Sites

3.2.1.1 Mbeere North

The experiment was done in Ishiara Ward in Mbeere North Sub-County, Embu County, Kenya. The zone is located to the East of Mount Kenya. The site is positioned at the latitude of 0°26'42"S and the longitude of 37°46'56"E, at an elevation of 852 metres above sea level—Mbeere North range of temperature from 15℃ to 30℃ with a mean temperature of 23℃. According to Gitari et al. (1999), the area has sandy, reddish brown and blackish-grey soils. The site receives bimodal precipitation with extended downpours from March to June, while short rains fall between October and December. A mean of 800 mm falls annually, extending from 500 mm to 1100 mm in total. However, the rainfall is not reliable. The precinct lies in the zone of agroecology known as Lower Midland 4 (LM 4), hot, dry and semi-arid land. The number of inhabitants in the sub-county is approximately 108,881 people (KNBS, 2019), with a mean farm size of approximately 6.5 hectares (Gachimbi et al., 2007).

3.2.1.2 Mbeere South Sub-County

Kiamuringa sub-location, Mbeere South Sub-County, Embu County, was the study's execution site. The Sub-county covers an area of 1,321.5 km^2 (Ngetich *et al.*, 2014) and extends to Lower Midland Zones three, four, and five (LM 3; LM 4, and LM 5) agro-ecological zones (Njeru et *al.*, 2013). The number of inhabitants in the sub-county is approximately 163,476 people (KNBS, 2019). Due to the region's dual rainfall patterns, which feature two cropping seasons annually—long rains from mid-March to June and short rains from late October to December—there are two distinct growing seasons. The yearly rainfall average is between 700 and 900 millimetres. The experimental site was located at the latitude 0°34'18"S and longitude 37°32'10"E at a rise of approximately 1200 metres higher than the sea level. Between 21.7°C and 22.5°C is the range of the annual mean temperaturewith acrisols and ferralsols soils (Njeru et al., 2013).

3.2.1.3 Embu West Sub-County

Embu West (Manyatta) Sub-County, Embu County, Kangaru Ward (University of Embu) was the location of the experiment. According to Mugendi *et al*. (2007), The research region is located within Upper Midlands 2 and 3 (UM 2 and UM 3), characterized by warm and humid climates predominated by maize, beans, and banana production. The site lies at latitude 0°30'56"S and longitude 37°27'22"E lies within an altitude of approximately 1490 metres above sea level. The annual temperature is about 20°C, with yearly rainfall varying from 909 mm to 1230 mm (Njeru *et al*., 2013). Bimodal rainfall occurs in the region in two distinct periods: April through June brings long rains, and October through December brings short rains (Njeru et al., 2013). Most soils have humic properties, such as nitisols, which are characterized by deep, well-weathered, and moderate fertility. According to Mugendi *et al*. (2007), there are low phosphate, nitrogen, and organic carbon concentrations and slightly acidic soil pH. Maize growing is predominant in Embu West Sub County, which has small landholdings and an average of 1.2 hectares per household. The sub-county's inhabitants are approximately 127,100 people (KNBS, 2019). The study sites are shown in Figure 3.1.

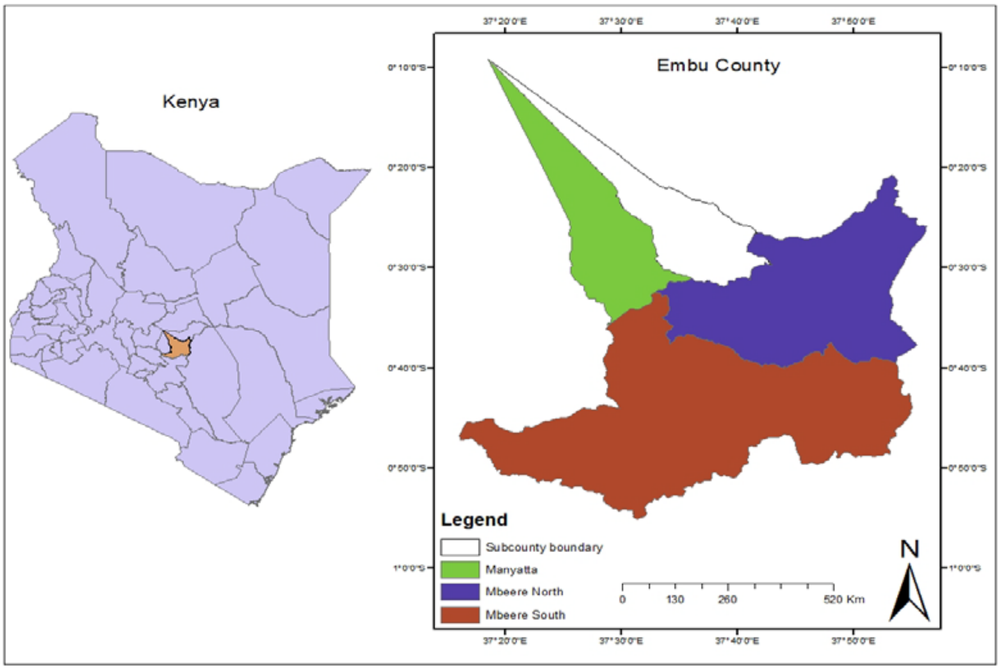

Figure 3.1: Map of the study area

3.2.2 Experimental design

The experimentation was performed in all three sites described in section 3.2. Bambara groundnut landraces were gathered from farmers in Western Kenya (Table 3.1). The research was conducted between October and December 2019 during the short rain spell and between March and May 2020 during the long rain season. In the split-plot experimental setting, a randomised complete block design was used, which was replicated three times. The three population densities (S1 = 50 cm × 20 cm, S2 = 50 cm x 30 cm, and S3 = 50 cm x 40 cm) comprised the primary plots, while sub-plots were the three selected landraces: BG 005, BG 003 and BG 001. Each plot measured 2 m x 2 m and composed of three rows. Two seeds were planted five centimetres down each hill, and three weeks after the emergency, the number of plants was reduced to one per hill. Additional agronomic practices were done uniformly in all experimental plots.

Table 3.1: Sources of Bambara groundnut landraces and their agro-ecological factors

Landrace	**Source**	**Latitude**	**Longitude**	**Altitude (m a.s.l)**	**Annual rainfall (mm)**	**Mean Temp.** (°C)	**Dominating soil type**
BG 001	Vihiga	0º 15'	34º 40'	1950	1900	24	Acrisols
BG-003	Kakamega	0º 53'	35º 09'	1500	1500	21	Luvisols
BG-005	Busia	0º 47'	33º 57'	1300	1691	25	Loamy

3.2.3 Data Collection

Data collected included: plant spread, plant height, branch number, mean seed length, mean seed width, number of seeds per pod, length and width of pods on a plant, number of pods per plant, 100 grain mass, total grain yield, and leaf area index. Plant spread was recorded ten weeks after planting by measuring the longest distance separating two opposing points, and an average of five plants was recorded. The plant's height was measured from the ground level of the plant and ending at the terminal leaflet. Five plants' average height was noted. The number of branches on each stem was measured at harvest by counting the branches of the three main stems of five healthy plants, and the average was recorded. The methods are guided by According to the International Plant Genetic Resources Institute (1997). Leaf area index (LAI) was estimated at ten weeks after seeding using the formula of Sparkes (2003) as shown below:

$$\boldsymbol{L = N_P x\, N_1\ X\, A_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.1)}$$

The variables Np, N1, and A1 represent the number of plants per unit area, the number of leaves per plant, and the average area per leaf, respectively.

Ten pods were measured for length and breadth at harvest using a Vernier calliper, and the average was recorded. When ten plants were harvested, the quantity of pods on each plant was tallied, and the average was noted. By averaging the number of seeds in ten pods, it was determined how many seeds each pod contained. The seeds' length and width were obtained one month after harvest by taking the average length and width of 10 dry seeds with 12% moisture content using a Vernier calliper. The 100-seed weight was obtained one month after harvesting by taking the average weight of 100 dry seeds. Yield was taken by weighing dried seeds for all the plants.

3.2.4 Data Analysis

Data collected was analysed using three-way ANOVA to test the significant differences between the spacing, landraces, and sites and their interactions between seasons. Tukey Honestly Significant Difference (HSD) at P = 0.05 was done to separate treatment means.

3.3 Results

3.3.1 Growth of Bambara groundnut landraces at different spacings

3.3.1.1 Growth variations at the Kangaru site

At Kangaru site, the plant spacing influenced the plant spread of Bambara groundnut (Table 3.2). Spacing 3 (50 cm x 40 cm) recorded the most significant average plant spread of 170.83 cm, followed by spacing 2 (50 cm x 30 cm) with an average of 152.11 cm while spacing 1 (50 cm x 20 cm) obtained an average spread of 131.61 cm. The different spacings did not significantly (P>0.05) influence the height of the plant, the branch number, and the leaf area index (LAI) of Bambara groundnut (Table 3.2). In the same site, the plant height, plant spread and branch number varied significantly (P<0.05) amongst the tested Bambara groundnut landraces (Table 3.2). The landrace BG 001 recorded the longest plant height of 29.66 cm, followed by BG 003, with a plant height of 28.16 cm, while BG 005 recorded the least plant height of 26.02 cm. Landrace BG 005 obtained the maximum average plant spread of 171.67 cm, followed by BG 003 with an average spread of 146.00 cm, while BG 005 trailed with an average plant spread of 137.89 cm. Landrace BG 001 recorded the greatest average number of branches (29), followed by BG 003 with an average of 10 branches. At the same time, BG 005 produced the minimum number of branches (8). No significant ($P>0.05$) variation was observed in the leaf area index (LAI) among the tested landraces whose LAI ranged from 0.67 – 0.92 (Table 3.2). Seasonal variations were highly significant ($P<0.0001$) for plant height, where the highest average plant height of 29.96 cm stood recorded in season 2, whereas the average plant height in season 1 was 25.94 cm. Seasonal variations were significant ($P<0.05$) for plant spread, where the highest average plant spread of 155.44 cm was noted in season 2, while the average plant spread in season 1 was 153.04 cm. Seasonal variations were significant ($P<0.05$) for the plant height with season 2 recording an average plant height of 29.96 cm, while the average plant height in season 1 was 25.94 cm. No seasonal variations were observed in the count of branches and leaf area index of the growth parameters. The site possessed no significant ($P<0.001$) effect on landrace interactions or spacing.

Table 3.2: Spacing effect on the growth of Bambara groundnut landraces at Kangaru site

		Plant Height (cm)	**Plant Spread**	**Branch Number**	**LAI**
Main Factors (Spacing)	Spacing 1 (50 x 20 cm)	27.02	132.61 c	16.51	0.92
	Spacing 2 (50 x 30 cm)	28.10	152.11 b	16.44	0.70
	Spacing 3 (50 x 40 cm)	28.73	170.83 a	15.46	0.73
	P value	0.202	<0.001	0.741	0.453
	Standard Error	0.665	0.465	1.070	0.130
Sub-Plots (Landraces)	BG 001	29.67 a	137.89 c	29.56 a	0.92
	BG 003	28.17 b	146.00 b	10.84 b	0.76
	BG 005	26.02 c	171.67 a	8.01 b	0.67
	P value	0.002	<0.0001	<0.0001	0.417
	Standard Error	0.665	0.465	1.070	0.130
Seasonal Variations	Season 1	25.94 b	153.04 b	17.04	0.86
	Season 2	29.96 a	155.44a	15.24	0.71
	P value	<0.0001	<0.0001	0.155	0.31
	Standard Error	0.543	0.155	0.874	0.106
Spacing x Landrace Interactions (P Values)		0.119^{NS}	0.425^{NS}	0.506^{NS}	0.385^{NS}

Legend: NS = Not Significant; LAI = leaf area index. P =P value, Letters ‘a’ and ‘b’ indicate statistically significant difference found by honest significance difference Tests ($p< 0.05$).

3.3.1.2 Growth variations at Ishiara site

At Ishiara site, spacing recorded a highly significant (P<0.0001) effect on the average plant spread (Table 3.3). Spacing 2 (50 cm x 30 cm) recorded the most significant average plant spread of 196.78 cm, followed by spacing 1 (50 cm x 20 cm) with an average of 185.06 cm while spacing 3 (50 cm x 40 cm) obtained an average spread of 184.72 cm. In the same site, there were significant variations (P<0.0001) amongst the three tested Bambara groundnut landraces for all the growth variables that were evaluated except the leaf area index (LAI) (Table 3.3). The landrace BG 003 recorded the tallest plant height of 34.86 cm, followed by BG 001, with a mean height of 34.27 cm, while BG 005 attained an average plant height of 29.73 cm. Regarding plant spread, the landrace BG 005 had the longest average plant spread of 199.56 cm, followed by BG 003 with an average spread of 190.33 cm, while BG 001 trailed with an average plant spread of 176.67 cm. The landraces recorded significant (P<0.001) difference in the average number of branches (Table 3.3). Landrace BG 001 attained the greatest number of 40 branches, followed by BG 003 with an average number of branches of 22, while BG 005 trailed with an average of 18 branches. The landraces did not record any significant (P<0.001) difference in the average leaf area index (LAI) (Table 3.3).

Seasonal variations was significant (P<0.05) for plant height, where the highest average plant height of 36.27 cm was attained in season 1, while the average plant height in season 2 was 29.63 cm. Seasonal variations were significant (P<0.05) for plant spread, where the longest average plant spread of 174.03 cm was obtained in season 1, while the average plant spread in season 2 was 159.23 cm. At Ishiara site, there was no significant (P<0.0001) seasonal variations for the branch number and LAI.

Table 3.3: Spacing effect on the growth of Bambara groundnut landraces at Ishiara site

Factors	Treatments	Plant Height (cm)	Plant Spread	Branch Number	LAI
Main Factors (Spacing)	Spacing 1 (50 x 20 cm)	33.12	185.06 b	26.94	0.82
	Spacing 2 (50 x 30 cm)	32.74	196.78 a	26.83	0.83
	Spacing 3 (50 x 40 cm)	33.02	184.72 b	27.09	2.50
	P value	0.834	<0.0001	0.987	0.136
	Standard Error	0.466	0.765	1.137	0.663
Sub-Plots (Landraces)	BG 001	34.27 a	176.67c	40.18 a	0.84
	BG 003	34.86 a	190.33b	22.35 b	2.50
	BG 005	29.73 b	199.56a	18.32 c	0.80
	P value	<0.0001	<0.0001	<0.0001	0.134
	Standard Error	0.466	0.765	1.137	0.663
Seasonal Variations	Season 1	36.27 a	174.03 a	28.24	1.39
	Season 2	29.63 b	159.23 b	25.66	1.37
	P value	<0.0001	<0.0001	0.057	0.983
	Standard Error	0.380	0.876	0.928	0.541
Spacing x Landrace Interactions (P Values)		0.957^{NS}	0.087^{NS}	0.986^{NS}	0.100^{NS}

Legend: LAI = leaf area index; NS = Not Significant; Letters ‘a’ and ‘b’ indicate statistically significant difference found by honest significance difference Tests (p< 0.05).

3.3.1.3 Growth variations at Kiamuringa site

At Kiamuringa site, the different spacings significantly (P<0.05) influenced plant spread of Bambara groundnut (Table 3.4). Spacing 3 (50 cm x 40 cm) resulted to maximum plant spread of 204.83 cm, followed by spacing 2 (50 cm x 30 cm) with an average of 183.78 cm while spacing 1 (50 cm x 20 cm) obtained an average spread of 154.44 cm. In the same site, there were highly significant (P<0.0001) variations amongst the three tested landraces of Bambara groundnuts for every growth variable evaluated (Table 3.4). Landrace BG 003 recorded the tallest plant height of 33.24 cm, followed by BG 001, with a plant height of 32.17 cm, while BG 005 obtained an average plant height of 27.04 cm. The landrace BG 005 had the longest plant spread of 211.56 cm, followed by BG 003 with an average spread of 187.67 cm, while BG 001 scored the least plant spread of 143.83 cm. The landrace BG 001 obtained the greatest number of 27 branches, followed by BG 003 with an average number of branches of 20, while BG 005 obtained an average of 14 branches. Landrace BG 001 recorded the highest average leaf area index (LAI) of 0.84, followed by BG 003, with an average leaf area index of 0.79, while BG 005 obtained an average leaf area index of 0.77. Seasonal variations were significant ($P<0.05$) for plant height, where the highest average plant height of 38.14 cm was noted in season 1, whereas the average plant height in season 2 was 23.49 cm.

Seasonal variations were highly significant ($P<0.0001$) for plant spread, where the highest average plant spread of 186.69 cm was obtained in season 1, while the average plant spread in season 2 was 173.83 cm. Seasonal variations were highly significant ($P<0.0001$) for plant height, where the longest mean plant height of 38.14 cm was noted in season 1, although the height of the plant in season 2 was 23.49 cm. Seasonal variations were also significant ($P<0.05$) for the number of branches per plant, where the highest average number of 22 branches was recorded in season 1, while the the number of branches for every plant in the second season was 19. There were significant ($P>0.05$) seasonal variations for leaf area index at Ishiara site (Table 3.4).

Table 3.4: Spacing effect on the growth of Bambara groundnut landraces at Kiamuringa

Factors	Treatments	Plant Height (cm)	Plant Spread	Branch Number	LAI
Main Factors (Spacing)	Spacing 1 (50 x 20 cm)	31.41	154.44 c	20.73	0.81
	Spacing 2 (50 x 30 cm)	30.59	183.78 b	19.13	0.79
	Spacing 3 (50 x 40 cm)	30.44	204.83 a	20.92	0.80
	P value	0.281	<0.001	0.380	0.404
	Standard Error	0.462	0.562	0.984	0.007
Sub-Plots (Landraces)	BG 001	32.17 a	143.83 c	26.86 a	0.84 a
	BG 003	33.24 a	187.67 b	20.03 b	0.79 b
	BG 005	27.04 b	211.56 a	13.88 c	0.77 b
	P value	<0.0001	<0.0001	<0.0001	<0.0001
	Standard Error	0.462	0.562	0.984	0.007
Seasonal Variations	Season 1	38.14 a	186.69 a	21.69 a	0.80
	Season 2	23.49 b	173.83 b	18.83 b	0.80
	P value	<0.0001	<0.0001	<0.0017	1.000
	Standard Error	0.377	0.768	0.803	0.798
Spacing x Landrace Interactions (P Values)		0.332^{NS}	0.244^{NS}	0.244^{NS}	0.039^{NS}

Legend: LAI = leaf area index; NS = Not Significant; Letters 'a' and 'b' indicate statistically significant difference found by honest significance difference Tests ($p< 0.05$).

3.3.1.4 Average growth of Bambara groundnut over the three sites

In the three sites, the plant spacing was significant ($P<0.001$) on the plant spread of Bambara groundnut (Table 3.5). Spacing 3 (50 cm x 40 cm) had the most significant plant spread of 202.43 cm, followed by spacing 2 (50 cm x 30 cm) with an average of 178.78 cm while spacing 1 (50 cm x 20 cm) obtained an average spread of 163.64 cm. There was no significant ($P>0.001$) spacing effect on the height of the plant, the leaf area index (LAI), and the number of branches of Bambara groundnut. There was a significant ($P<0.0001$) effect on the three tested Bambara groundnut landraces for each of the growth variables that were evaluated (Table 3.5). Landrace BG 003 recorded the tallest plant height of 32.59 cm, followed by BG 001 with a mean plant height of 31.54 cm, while BG 005 obtained th least plant height of 27.60 cm. Landrace BG 005 had the most extended average plant spread of 192.76 cm, followed by BG 003, with an average spread of 181.33 cm, while BG 001 had the least with an average plant spread of 173.67 cm. Landrace BG 001 had the maximum number of 32 branches, followed by BG 003 with an average of 18 branches, while BG 005 trailed with an average number of 13 branches. The landraces did not record significant ($P>0.001$) differences in the average leaf area index (Table 3.5).

Combined analysis also recorded significant ($P<0.0001$ site variations for all the growth parameters evaluated except the leaf area index. Ishiara site recorded the highest height of the plant at 32.95 cm, followed by Kiamuringa, which achieved the average height of the plant of 30.81 cm, while Kangaru obtained the least plant height of 27.95 cm. Kangaru site recorded the highest plant spread of 203 cm, followed by Kiamuringa site with an average plant spread of 174.67 cm, while Kangaru site obtained an average plant spread of 155.83 cm. Ishiara site obtained the highest branch number of 27, followed by the Kiamuringa site, which had an average number of 20 branches, while the Kangaru site obtained an average number of 16. The sites did not record significant ($P>0.05$) differences in the average leaf area index (Table 3.5).

There were significant ($P<0.0001$) seasonal variations for all the growth variables evaluated except leaf area index. The highest average plant height of 33.45 cm was achieved in season 1, though the average plant height in season 2 was 27.67 cm. The highest plant spread of 182.32 cm was recorded in season 1, while the average plant spread in season 2 was 169.91 cm. Season 1 also had the greatest average quantity of branches on a single plant of 22, while the average branch quantity for each plant in season 2 was 20. There were significant seasonal variations for the leaf area index in the combined analysis (Table 3.5).

Table 3.5: Spacing effect on the Bambara groundnut growth landraces for all three sites combined

Factors	**Treatments**	**Plant Height (cm)**	**Plant Spread**	**Branch Number**	**LAI**
Main Factors (Spacing)	Spacing 1	30.52	163.64c	21.39	0.85
	Spacing 2	30.47	178.78b	20.80	0.78
	Spacing 3	30.73	202.43a	21.16	1.34
	P value	0.830	<0.0001	0.803	0.167
	Standard Error	0.317	0.636	0.636	0.228
Sub-Plots (Landraces)	BG 001	31.53 a	173.67c	32.20 a	0.81
	BG 003	32.59 a	181.33b	17.74 b	1.40
	BG 005	27.59 b	192.76a	13.40 c	0.74
	P value	<0.0001	<0.0001	<0.0001	0.088
	Standard Error	0.317	0.636	0.636	0.228
Site Variations	Ishiara	32.95 a	155.83 c	26.95 a	1.38
	Kiamuringa	30.81 b	174.67 b	20.25 b	0.79
	Kangaru	27.95 c	203.56 a	16.13 c	0.78
	P value	<0.0001	<0.0001	<0.0001	0.113
	Standard Error	0.317	0.636	0.636	0.228
Seasonal Variations	Season 1	33.45 a	182.32 a	22.32 a	1.01
	Season 2	27.69 b	169.91 b	19.91 b	0.96
	P value	<0.0001	<0.0001	<0.0001	0.830
	Standard Error	0.259	0.481	0.520	0.187
Spacing x Landrace Interactions (P Values)		0.994^{NS}	0.781 ^{NS}	0.670 ^{NS}	0.157^{NS}

Legend: NS = Not Significant; LAI = leaf area index; Letters ‘a’ and ‘b’ indicate statistically significant difference found by honest significance difference Tests (p< 0.05).

3.3.2 Yield of Bambara groundnut landraces at different spacings

3.3.2.1 Yield variations at Kangaru site

At Kangaru site, the plant spacing was significant (P<0.05) on the number of pods and the seeds number per plant of Bambara groundnut (Table 3.6). Spacing 3 (50 cm x 40 cm) had the highest average pod number of 26, followed by spacing 2 (50 cm x 30 cm)with an average of 24 pods per plant, while spacing 1 (50 cm x 20 cm) obtained an average of 20 pods per plant. Spacing 3 (50 cm x 40 cm) recorded the highest number of seeds (27), followed by spacing 2 (50 cm x 30 cm) with an average of 23, while spacing 1 (50 cm x 20 cm) obtained an average of 20 seeds. The plant spacing had no significant (P>0.05) effect on pod length, the number of seeds per pod, pod width, the width of seeds, length of seeds, the weight of 100 seeds, and the overall seed yield (Table 3.6).

There were significant ($P<0.05$) variations amongst the tested Bambara groundnut landraces on the number of pods and seeds on each plant, average pod width, seed length, 100 seeds weight, and the overall seed yield, while the number of seeds in a pod recorded significant ($P<0.05$) divergences between the tested landraces (Table 3.6). Landrace BG 001 obtained the most pods (44) per plant, followed by BG 003 and BG 005, with an average of 13 pods each. Landrace BG 003 had the highest average pod width of 1.33 cm, followed by BG 001 with an average pod width of 1.20 cm, while BG 005 trailed with an average pod width of 1.02 cm. Landrace BG 001 had the highest average seeds per plant (45), followed by BG 005 with an average of 14 seeds, while BG 003 trailed with an average of 13 seeds per plant.

All the landraces had an average of a single seed per pod. Landrace BG 001 had the highest average seed length of 1.20 cm, followed by BG 003 with 1.13 cm, while BG 005 recorded the lowest with 1.04 cm. In addition, BG 001 had the highest average weight of 100 seeds (58.28 g), followed by BG 003 with an average of 43.07 g, while BG 003 trailed with an average of 42.12 g. Further, BG 001 had the greatest average seed yield of 5.30 ton ha^{-1}, followed by BG 003 with an average of 1.22 ton ha-1, while BG 003 trailed with an average yield of 1.21 ton ha-^{1}. The three landraces also did not record significant ($P<0.001$) differences in the average length of pods and seed width (Table 3.6). Seasonal variations were not significant ($P>0.05$) for all the Bambara groundnut landrace yield components. Landrace and spacing interactions were significant for the pod number per plant, number of seeds per pod and seed length (Table 3.6).

Table 3.6: Spacing effect on the yield components of different Bambara groundnut landraces at Kangaru site

Factors	Treatments	Pod Number	Pod Length (cm)	Pod Width (cm)	Seeds per Plant (No.)	Seeds per Pod (No.)	Seed Length (cm)	Seed Width (cm)	Weight of 100 Seeds (grams)	Seed Yield (t/ha)
Main Factors (Spacing)	Spacing 1	20.87 c	2.32	1.27	20.73c	1.03	1.10	1.35	48.44	3.46
	Spacing 2	24.31 ab	1.75	1.12	23.92b	1.04	1.11	1.20	48.55	2.51
	Spacing 3	26.88 a	1.47	1.15	27.40a	1.04	1.17	0.86	48.50	2.19
	P value	0.005	0.276	0.393	0.018	0.920	0.056	0.672	0.589	0.113
	Standard Error	1.218	0.376	0.080	1.561	0.017	0.020	0.401	1.509	0.844
Sub-Plots (Landraces)	BG 001	44.71 a	2.14	1.20 ab	44.90 a	1.06 a	1.20 a	1.48	58.28 a	5.30 a
	BG 003	13.59 b	2.05	1.33 a	12.89 b	1.00 b	1.13 b	1.25	42.12 b	1.22 b
	BG 005	13.76 b	1.35	1.02 c	14.25 b	1.04 b	1.04 c	0.68	43.07 b	1.21 b
	P value	<0.0001	0.280	0.036	<0.0001	0.025	<0.0001	0.359	<0.0001	<0.0001
	Standard Error	1.218	0.376	0.080	1.561	0.017	0.020	0.401	1.509	0.844
Seasonal Variations	Season 1	24.44	2.21	1.22	24.81	1.02	1.12	1.46	47.82	3.98
	Season 2	23.60	1.47	1.14	23.22	1.04	1.13	0.81	47.83	2.51
	P value	0.558	0.097	0.402	0.385	0.274	0.943	0.166	0.997	0.549
	Standard Error	0.994	0.307	0.065	1.275	0.014	0.016	0.327	1.232	0.844
Spacing x Landrace Interactions (P Values)		< 0.001	0.593^{NS}	0.488^{NS}	0.832^{NS}	<0.001	0.011	0.274^{NS}	0.543^{NS}	0.083^{NS}

Legend: NS = Not Significant**;** Letters ‘a’ and ‘b’ indicate statistically significant difference found by Honest Significance Difference Tests (p< 0.05).

3.3.2.2 Yield variations at Ishiara site

At Ishiara site, the plant spacing was significant ($P<0.001$) on the weight of 100 seeds of Bambara groundnut (Table 3.7). Spacing 3 (50 cm x 40 cm) recorded the highest weight of 100 seeds (58.56 g), followed by spacing 2 with 54.24 g and spacing 1 (50 cm x 20 cm) with an average of 50.42 g. Plant spacing was found to have no significant ($P>0.05$) effect on the rest of the yield components (Table 3.7). The landraces were found to have significant ($P<0.001$) variations pod number, average pod length, seed length, weight of 100 seeds, seed number per plant, and overall yields (Table 3.7). Landrace BG 001 had the highest average pod number of 87, followed by BG 003 with an average pod number of 68, while BG 005 had the lowest average pod number of 42. Further, BG 001 had the highest pod length of 1.58 cm, followed by BG 003 and BG 005, both with average pod length of 1.37 cm. Moreover, BG 001 had the highest average seeds per plant of 88, followed by BG 003 with an average of 70 seeds per plant, while BG 005 trailed with an average of 45 seeds per plant. Nevertheless, BG 001 had the longest average seed length of 1.13 cm, followed by BG 003 with an average of 1.05 cm, while BG 005 recorded the least with an average of 0.96 cm. Moreover, BG 001 had the highest average weight of 100 seeds (59.40 g), followed by BG 003 with 56.05 g, while BG 005 trailed with an average of 47.77 grams. The landrace BG 001 had the highest average seed yield of 10. 86 ton ha-1, followed by BG 003 with seeds yields of 8.54 ton ha-1, while BG 005 trailed with an average yield of 4.96 ton ha^{-1}. The landraces did not portray significant ($P>0.05$) variations in the width of pods, seeds per pod, and seed width (Table 3.7).

There were also highly significant ($P<0.0001$) seasonal variations for pod number, pod length, seeds per plant, and grain yields. Season 2 reported the plant with the fewest pods of 53, whereas season 1 recorded the utmost number of 77 pods per plant. The greatest average number of seeds per plant (80) per plant was recorded in season 1, while the average number of seeds (55) was recorded in season 2. The greatest average grain yield of 12.12 tons ha-1 was recorded in Season 1, whereas the average grain yield of 6.83 tons ha^{-1} in season 2. The highest average pod length of 1.50 cm was obtained in season 1, whereas the average pod length of 1.40 cm was noted in season 2. Seasonal variations were not significant ($P>0.05$) in length, width, seeds per pod, seeds in a pod, and 100 grains weight of Bambara groundnuts. The spacing x landrace interactions had a significant ($P<0.05$) effect on the number of seeds per plant and the seed's width. The spacing x landrace interactions did not significantly ($P>0.05$) influence the pod number per plant, length, width, and number of seeds in each pod, 100-grain weight, and seed yields.

Table 3.7: Spacing effect on the yield components of different Bambara groundnut landraces at Ishiara site

Factors	Treatments	Pod Number	Pod Length (cm)	Pod Width (cm)	Seeds per Plant (No.)	Seeds per Pod (No.)	Seed Length (cm)	Seed Width (cm)	Weight of 100 Seeds (grams)	Seed Yield (t/ha)
Main Factors (Spacing)	Spacing 1	72.14	1.45	1.02	74.41	1.04	1.06	0.73	54.24b	13.67
	Spacing 2	64.59	1.43	1.03	65.75	1.07	1.02	0.72	50.42c	7.40
	Spacing 3	60.97	1.46	1.08	63.77	1.05	1.06	0.83	58.56a	5.88
	P value	0.108	0.836	0.153	0.166	0.166	0.689	0.498	0.010	0.130
	Standard Error	3.695	0.031	0.024	4.111	0.024	0.025	0.075	1.778	3.016
Sub-Plots (Landraces)	BG 001	87.46 a	1.58 a	1.07	88.05 a	1.04	1.13 a	0.76	59.40 a	10.86 a
	BG 003	68.18 b	1.37 b	1.00	70.41 b	1.03	1.05 b	0.72	56.05 a	8.54 b
	BG 005	42.06 c	1.38b	1.05	45.46 c	1.08	0.96 b	0.79	47.77 b	4.96 c
	P value	<0.0001	<0.0001	0.110	<0.0001	0.214	0.001	0.843	0.001	<0.0001
	Standard Error	3.695	0.031	0.024	4.111	0.024	0.025	0.075	1.778	3.016
Seasonal Variations	Season 1	77.88 a	1.49 a	1.05	80.94 a	1.04	1.06	0.73	54.43	12.12 a
	Season 2	53.92 b	1.39 b	1.03	55.01 b	1.06	1.04	0.79	54.38	6.83b
	P value	<0.0001	0.010	0.396	<0.0001	0.439	0.427	0.511	0.981	0.001
	Standard Error	3.017	0.026	0.019	3.357	0.019	0.020	0.061	1.452	2.463
Spacing x Landrace Interactions (P Values)		0.100^{NS}	0.307^{NS}	0.317^{NS}	0.016	0.650^{NS}	0.665^{NS}	0.004	0.371^{NS}	0.957^{NS}

Legend: NS = Not Significant; Letters ‘a’ and ‘b’ indicate statistically significant difference found by Honest Significance Difference Tests (p< 0.05).

3.3.2.3 Yield variations at Kiamuringa site

Plant spacing had no significant (P>0.05) effect on yield components (Table 3.8). However, the landraces showed significant (P<0.0001) variations in all the yield components except the seed number per pod (Table 3.8). Landrace BG 001 had the highest average pod number of 53, followed by BG 003 with an average pod number of 47, while BG 005 trailed with an average pod number of 26. Furthermore, BG 001 had the highest average length of pods of 1.73 cm, followed by BG 003 with 1.51 cm, and lastly BG 005 with an average of 1.19 cm. In addition, BG 001 performed best with an average pod width of 1.28 cm, followed by BG 003, which recorded 1.06 cm, and lastly BG 005, with an average pod width of 0.79 cm. Landrace BG 001 recorded the highest average number of 55 seeds per plant, followed by BG 003 with an average of 48 seeds, while BG 005 trailed with an average of 25 seeds per plant. The landrace BG 001 had the longest average seed length of 1.31 cm, followed by BG 003 with an average of 1.09 cm, while BG 005 trailed with an average of 0.84 cm.

Landrace BG 001 performed best with an average seed width of 1.00 cm, followed by BG 003 with an average of 0.91 cm, while BG 005 had the lowest average of 0.54 cm. The landrace BG 001 had the highest average weight of 100 seeds at 59.27 g, followed by BG 003 with 49.88 g, while BG 005 trailed with 40.95 g. The landrace BG 001 had the highest average seed yields of 6.69 ton ha-1, followed by BG 003 with 5.11 6.69 ton ha-1, while BG 005 was the least with 2.45 6.69 ton ha^{-1}. Seasonal variations were highly significant (P<0.0001) for the count of pods per plant, pod length, number of seeds per plant, weight of 100 seeds, and overall yield. First season had the highest average number of 45 pods per plant compared to the second season that had 39 pods per plant. The average pod length was 1.55 cm in season 1 compared to 1.41 cm in season. The highest number of seeds (47) was obtained in season 1, while season 2 recorded an average of 38 seeds per plant in season 2. The weight of 100 seeds averaged 54.44 g in season 1 compared to 45.61 g in season 2. The greatest average yield of 5.51 ton ha^{-1} was obtained in season 1 compared to 3.99 ton ha^{-1} in season 2. Seasonal variations were not significant (P>0.05) for seeds per pod, seed length, and seed width. The spacing x landrace interactions were insignificant (P>0.05) on yield in the Kiamuringa site except on the width of pods.

Table 3.8: Spacing effect on the yield components of different Bambara groundnut landraces at Kiamuringa site

Factors	Treatments	Pod Number	Pod Length (cm)	Pod Width (cm)	Seeds per Plant (No.)	Seeds per Pod (No.)	Seed Length (cm)	Seed Width (cm)	Weight of 100 Seeds (grams)	Seed Yield (t/ha)
Main Factors (Spacing)	Spacing 1	43.93	1.51	1.03	43.61	1.08	1.06	0.78	48.94	7.30
	Spacing 2	41.71	1.47	1.06	42.63	1.09	1.09	0.76	51.19	4.76
	Spacing 3	40.95	1.45	1.03	42.05	1.04	1.10	0.91	49.94	4.63
	P value	0.568	0.633	0.641	0.896	0.436	0.300	0.095	0.587	0.876
	Standard Error	2.040	0.051	0.024	2.387	0.028	0.019	0.052	1.530	1.608
Sub-Plots (Landraces)	BG 001	53.45 a	1.73 a	1.28 a	55.09 a	1.10	1.31 a	1.00 a	59.24 a	6.69 a
	BG 003	47.33 a	1.51 b	1.06 b	47.88 a	1.09	1.08 b	0.91 a	49.88 b	5.11 b
	BG 005	25.81 b	1.19 c	0.79 c	25.31 b	1.02	0.84 c	0.54 b	40.95 c	2.45 c
	P value	<0.0001	<0.0001	<0.0001	<0.0001	0.11	<0.0001	<0.0001	<0.0001	<0.0001
	Standard Error	2.040	0.051	0.024	2.387	0.028	0.019	0.052	1.530	1.608
Seasonal Variations	Season 1	44.951 a	1.54 a	1.06	47.38 a	1.08	1.07	0.82	54.44 a	5.51 a
	Season 2	39.443 b	1.41 b	1.02	38.14 b	1.07	1.09	0.81	45.61 b	3.99 b
	P value	0.025	0.024	0.113	<0.0001	0.822	0.428	0.897	<0.0001	0.000
	Standard Error	1.666	0.041	0.020	1.949	0.023	0.016	0.043	1.249	1.313
Spacing x Landrace Interactions (P Values)		0.183^{NS}	0.058^{NS}	0.014	0.221^{NS}	0.666^{NS}	0.993^{NS}	0.069^{NS}	0.277^{NS}	0.083^{NS}

Legend: NS = Not Significant; Letters ‘a’ and ‘b’ indicate statistically significant difference found by Honest Significance Difference Tests ($p < 0.05$).

3.3.2.4 Average yield of Bambara groundnuts over the three sites

A combined analysis of the three sites showed that the plant spacing had no significant ($P>0.05$) effect on all the yield components of Bambara groundnut (Table 3.9). Landraces portrayed highly significant ($P<0.0001$) variations in pod length, pod width, seed length, weight of 100 seeds, number of seeds per plant, and overall yields. Landraces also recorded significant ($P<0.05$) variation in the average pod number (Table 3.9). Landrace BG 001 had the highest average pod number of 62, followed by BG 003 with an average pod number of 43, while BG 005 trailed with an average pod number of 27. Further, BG 001 had the greatest length of pods (1.81 cm), followed by BG 003, which recorded an average pod length of 1.65 cm, and BG 005, with an average of 1.31 cm. Nevertheless, BG 001 had the highest average pod width of 1.18 cm, followed by BG 003, which recorded an average pod width of 1.13 cm, and BG 005 trailed with an average pod width of 0.96 cm. In addition, BG 001 recorded the longest seed length of 1.22 cm, followed by BG 002 with an average of 1.09 cm, while BG 005 obtained an average seed length of 0.95 cm. The landrace BG 001 recorded the highest average number of seeds produced by a plant of 63, followed by BG 002 with an average of 44 seeds, while BG 005 obtained an average of 28 seeds per plant. The weight of 100 seeds was highest in BG 001 (58.98 g), followed by BG 002 with an average of 49.36 g, while BG 005 obtained an average of 43.93 g from 100 seeds. The landrace BG 001 gave the best yields of 6.02 ton ha^{-1}, followed by BG 002 with an average of 4.96 ton ha$^{-1,}$ while BG 005 obtained an average seed yield of 2.87 ton ha^{-1}.

The combined analysis also revealed highly significant site variations in pod width, pod count for each plant, seed length, count of seeds per plant, one hundred seed weight, and overall yield. Kangaru site recorded a pod width of 1.19 cm, followed by the Ishiara site with an average pod length of 1.05 cm, while Kiamuringa site recorded an average pod width of 1.03 cm. Ishiara site recorded the greatest number of 66 pods per plant , followed by the Kiamuringa site with an average of 42 pods per plant, while the Kangaru site obtained an average of 24 pods per plant. The Kangaru site recorded the highest seed length of 1.13 cm, followed by the Kiamuringa site, with an average seed length of 1.08 cm, while the Ishiara site obtained a seed length of 1.05 cm. Ishiara site recorded the highest number of seeds of 67 per plant, followed by the Kiamuringa site with an average of 42 seeds per plant, while the Kangaru site obtained the least average of 24 seeds per plant. Ishiara site recorded the highest weight of 100 seeds at 54.41 g, followed by Kiamuringa site with an average weight of 50.02 g for 100 seeds, while Kangaru site obtained an average of 47.83 g. Ishiara site recorded the highest seed yield of 8.12 tons ha^{-1}, followed by the Kiamuringa site with an average seed weight of 4.75 tons ha-1, while the Kangaru site obtained a seed yield of 2.58 tons ha^{-1}.

Seasonal variations were significant ($P<0.05$) for pod length and the weight of 100 seeds, as well as highly significant ($P<0.0001$) for the number of pods on a plant, seeds per plant, and overall yield (Table 3.9). The longest pod length of 1.75 cm was recorded in season 1, while the average pod length in season 2 was 1.43 cm. An average pod width of 1.11 cm was recorded in season 1 compared to 1.06 cm in season 2. Similarly, the first season gave the highest number of seeds per plant (52) compared to an average of 39 seeds per plant obtained in season 2. The average number of pods per plant was significantly higher (51) in season 1 compared to season 2, where a mean of 39 pods per plant was obtained. The greatest average weight of 100 seeds, 29.29 g, was recorded in season 1, while the average weight of 100 seeds in season 2 was 22.20 g. The average overall yield per plant, where the maximum average seed yield of 5.86 ton ha-1, was noted in season 1, while the average seed yield in season 2 was 4.44 ton ha^{-1} (Table 3.9). Seasonal variations were insignificant ($P<0.05$) for seed width, seeds per pod, and seed length.

Landrace x site interactions were significant ($P<0.05$) for the pod width, number of pods per plant, seeds per pod, seed length, seeds per plant, weight of 100 seeds, and overall yield. The spacing x site interactions were significant ($P<0.05$) for the number of pods per plant. Spacing x landrace interactions were not significant ($P<0.001$) for all the yield components of Bambara groundnuts that were assessed in this study (Table 3.9).

Table 3.9: Spacing effect on the yield components of different Bambara groundnut landraces for all three sites combined

Factors	**Treatments**	**Pod Length (cm)**	**Pod Width (cm)**	**Pod Number**	**Seed Width (cm)**	**Seeds per Pod (No.)**	**Seed Length (cm)**	**Seeds per Plant (No.)**	**Weight of 100 Seeds (grams)**	**Seed Yield (t/ha)**
Main Factors (Spacing)	Spacing 1	1.76	1.11	45.65	0.96	1.05	1.07	46.25	50.54	8.14
	Spacing 2	1.563	1.07	43.54	0.89	1.07	1.08	44.09	49.39	4.89
	Spacing 3	1.453	1.09	42.93	0.87	1.04	1.11	44.41	52.33	4.00
	P value	0.267	0.698	0.430	0.904	0.351	0.111	0.651	0.093	0.348
	Standard Error	0.132	0.029	1.546	0.140	0.014	0.012	1.776	0.952	1.305
Sub-Plots (Landraces)	BG 001	1.82 a	1.18 a	61.88 a	1.08	1.07	1.22 a	62.68 a	58.97 a	6.02 a
	BG 003	1.65 b	1.13 a	43.03 b	0.96	1.04	1.09 b	43.73 b	49.35 b	4.96 b
	BG 005	1.31 b	0.96 b	27.21 c	0.67	1.05	0.953 c	28.34 c	43.93 c	2.87 c
	P value	0.024	<0.0001	<0.0001	0.107	0.302	<0.0001	<0.0001	<0.0001	<0.0001
	Standard Error	0.132	0.029	1.546	0.140	0.014	0.012	1.776	0.952	1.305
Site Variations	Ishiara	1.45	1.04 b	65.91 a	0.76	1.06	1.052 b	67.98 a	54.41 a	8.12 a
	Kiamuringa	1.47	1.03 b	42.19 b	0.82	1.07	1.081 b	42.76 b	50.02 b	4.75 b
	Kangaru	1.85	1.18 a	24.02 c	1.14	1.04	1.129 a	24.01 c	47.83 c	2.58 c
	P value	0.062	<0.0001	<0.0001	0.125	0.235	<0.0001	<0.0001	<0.0001	<0.0001
	Standard Error	0.132	0.029	1.546	0.140	0.014	0.012	1.776	0.952	1.305
Seasonal Variations	Season 1	1.75 a	1.11	49.09 a	1.01	1.05	1.09	51.05 a	52.23 a	5.86 a
	Season 2	1.43 b	1.07	38.99 b	0.81	1.06	1.09	38.79 b	49.27 b	4.44 b
	P value	0.035	0.143	<0.0001	0.215	0.468	0.931	<0.0001	0.008	<0.0001
	Standard Error	0.108	0.024	1.546	0.114	0.011	0.010	1.450	0.778	1.066
Interactions (P Values)	Spacing x Landrace	0.550^{NS}	0.412^{NS}	0.137^{NS}	0.209^{NS}	0.218^{NS}	0.279^{NS}	0.212^{NS}	0.107^{NS}	0.606^{NS}
	Landrace x Site	0.607^{NS}	<0.0001	<0.0001	0.522^{NS}	0.033	<0.0001	<0.0001	0.001	0.001
	Spacing x Site	0.338^{NS}	0.262^{NS}	0.038	0.669^{NS}	0.799^{NS}	0.379^{NS}	0.086^{NS}	0.065^{NS}	0.161^{NS}

Legend: NS = Not Significant; Letters ‘a’ and ‘b’ indicate statistically significant difference found by Honest Significance Difference Tests ($p < 0.05$).

3.4 Discussion

The aim of the study was to determine optimum spacing of Bambara groundnut. The significant spacing effect observed in this study for plant spread at Kangaru site could be attributed to minimal inter-species competition. The wider spacing of 50 x 40 cm might have reduced the competition of nutrients and other growth resources among the genotypes, thus encouraging a wider plant spread. Similar results were reported by Bernhard & Below (2020) in the United States, where wider inter-row spacing in corn resulted in increased plant growth components and, consequently, crop yields. The significant landrace effect observed in this study for plant spread at Kangaru site could be attributed to the adaptation of the Bambara groundnut landrace to the study area. The landrace of black Bambara groundnut had a higher ground cover compared to other landraces. The genetic makeup of the landraces and their adaptation to various growing conditions may cause the landraces' varying performance in plant dispersion (Berchie et al., 2012). The significant landrace effect on plant height at the Kangaru site can be attributed to the adoption of the Bambara groundnut landrace in the study area. The red-speckled and red Bambara groundnut landraces had a taller plant height. Karunaratne et al. (2010) on Bambara groundnut reported that variation in plant height among landraces could be attributed to superiority in adaptation of the landrace to the study area.

The significant landrace effect noted for the number of branches at Kangaru site could be attributed to the Bambara groundnut landrace possessing more canopy than other landraces. The red-speckled Bambara groundnut landraces had the highest number of branches because they had a large canopy. Plant height and the plant canopy are positively correlated. Karunaratne et al. (2011) reported that the difference in plant canopy among Bambara groundnut landraces is due to radiation levels that differ significantly and landraces' heterogeneity in growth and developmental processes. The significant seasonal effect on the plant height at Kangaru site can be attributed to variations in weather conditions. Long rains of the 2020 season recorded higher plant height, possibly due to favourable weather conditions, leading to increased growth. The significant seasonal effect on the plant spread at Kangaru site can be attributed to variations in weather conditions (appendix 2). Long rains of the 2020 season recorded higher plant spread, possibly due to favourable weather conditions (appendix 2), which increased growth. According to Mwale et al. (2007), variations in air temperature (26.6 ℃) and soil wetness (351.1 mm) may be the reason for canopy development variations in Bambara groundnuts.

The significant spacing effect observed in this study for plant spread at Ishiara site can be attributed to reduced competition (Harisha et al., 2024). A greater spacing of 50 x 40 cm reduced the competition of nutrients and other growth resources among the genotypes, thus encouraging a wider plant spread (Purnomo et al., 2024). Ngairangbam et al. (2024) indicated increased plant growth under larger spacing because there is less competition for resources like nutrients and water. A significant landrace effect for plant spread at the Ishiara site can be attributed to the adaptation of the landrace to the study site. The black landrace utilised the maximum environmental resources, which increased growth and encouraged a wider plant spread. Mohammed (2014), in Northern Nigeria, on Bambara groundnut landraces exhibited the most extended plant spread in landraces, which were well adapted to the study site, a semi-arid land.

Significant landrace effect in current research for the height of the plant and the number of branches at the Ishiara site could be attributed to the adaptation of the landraces to the site. The red speckled and the red landraces utilised the maximum environmental resources, increasing growth, thus encouraging a longer plant height and branch number. Berchie et al. (2012) recorded that Bambara groundnut can grow in dry environments with low nutrient concentrations. The significant season effect detected for the plant height at the Ishiara site can be attributed to variations in weather conditions. The short rains of the 2019 season recorded higher plant heights, possibly due to favorable weather conditions (Appendix 2), which led to increased growth. The significant season effect noted in the current study for the plant spread at the Ishiara site can be attributed to variations in weather conditions. Short rains of the 2019 season recorded higher plant spread due to favourable weather conditions (Appendix 2), which led to increased plant canopy. Sellami et al. (2021) reported that distinct landraces may arise and flourish under varying weather conditions throughout the year, allowing them to transform resources into yields.

Significant spacing effect observed in this study for plant spread at Kiamuringa site could be attributed to low competition for environmental resources. The wider spacing of 50 cm x 40 cm reduced the competition of nutrients and other growth resources among the genotypes, thus encouraging a wider plant spread. Chapepa et al. (2020) reported higher solar radiation interception from broader spacing, which increased the photosynthetic rate and higher total growth components. The significant landrace effect on the plant height at Kiamuringa site can be attributed to the adaptation of the landrace to the study site. The red landrace was well adapted to the environmental conditions, thus increasing the plant height. Chimonyo et al. (2020) noted that the higher growth components from Bambara groundnut landraces were due to better utilisation of resources in the study site. The significant landrace effect pointed out in this study for the plant spread at Kiamuringa site can be attributed to the good ground cover of the landrace. The black landrace of Bambara groundnut had a better ground cover than other landraces, with the most extended plant spread. Khan et al. (2021) stated that variations in plant canopy observed in Bambara groundnut landraces was due to the interaction of the genotype with the environment.

The significant landrace effect noted for the number of branches at Kiamuringa site could be attributed to the maximum utilisation of resources. The red-speckled Bambara groundnut landrace could have utilised the maximum environmental resources and, thus, the highest number of branches. Yakubu et al. (2010) recorded that when plants utilise natural resources such as light, space, and nutrients, they achieve maximum growth performance of the canopy. The significant landrace effect recorded for the leaf area index (LAI) at the Kiamuringa site could be attributed to having more excellent light interception. The red-speckled Bambara groundnut utilized the maximum environmental resources, increasing leaf expansion and, thus, the highest leaf area index. Akpalu et al. (2012) found that plants with effective light interception produced greater dry matter, hence a high leaf area index. A significant seasonal effect was observed on plant height, spread, and branch count.

The significant seasonal variations recorded on growth and yield of Bambara groundnuts at Kiamuringa site could be attributed to favourable weather conditions mainly precipitation and temperature (Appendix 2). The short rains season of 2019 performed better due to favourable weather conditions (Appendix 2) which enhanced growth of Bambara groundnut. Muhammad et al. (2020) indicated that Bambara groundnut landraces vary in growth components in different agroecological zones and seasons.

The significant spacing effect observed for the plant spread across the sites can be attributed to reduced inter-species competition. The wider spacing of 50 x 40 cm reduced the competition of nutrients and other growth resources among the genotypes, thus encouraging a wider plant spread. Gezahegn et al. (2016) noted that wider plant spacing increased plant canopy and general biomass. The significant landrace effect observed for the plant height across the sites can be attributed to the adaptation of the landrace to the study sites. The red landrace utilized the environmental resources optimally, which resulted in a taller plant canopy. Sabo et al. (2013) reported increased plant canopy height in plant genotypes that utilize maximum resources. The significant landrace effect observed for the plant spread across the sites can be attributed to the efficient utilization of available resources. The black landrace efficiently utilized the resources available among the genotypes, thus encouraging a wider plant spread. Zenabou et al. (2014) noted that different landraces influence the plant canopy size in Bambara groundnuts. The significant landrace effect observed for the number of branches across the sites can be attributed to the efficient utilization of available resources. The black landrace might have efficiently utilized the resources available among the genotypes, thus encouraging a large plant canopy. Razvi et al. (2018) showed that landraces contribute to growth character divergence among the plants.

The significant site effect observed for the plant height and branch count across the sites can be attributed to favorable environmental conditions in the study site (Appendix 2). Ishiara site provided favorable conditions for optimum growth among the genotypes, thus encouraging the highest plant height and branch count. The significant site effect observed for the plant spread across the sites is accredited to the disparity in weather conditions in the study site. Kangaru site provided favourable conditions for optimum growth among the genotypes, thus encouraging a wider plant spread. Yin et al. (2018) showed that different sites offer varied environmental conditions, which results in genotype diversity.

The significant season effect observed for the plant height, plant spread, and the number of branches across the sites can be attributed to variations in weather conditions. Long rains of 2020 season performed better possibly due to favourable weather conditions, which increased the growth components of Bambara groundnuts (Appendix 2). Massawe et al. (2003) noted that variation in performance on plant canopy among Bambara groundnut landraces could be attributed to variation in temperature. The significant spacing effect perceived for the pod number per plant at Kangaru site can be attributed to low competition for environmental resources. The wider spacing of 50 x 40 cm might have reduced the competition for nutrients and other growth resources among the genotypes, thus encouraging a high quantity of pods per plant. Tamiru et al. (2020) reported higher grain yields under wider spacing in chickpea.

The significant spacing effect observed for the number of seeds at Kangaru site could be attributed to relatively higher rainfall and low temperatures which may have created some stress during podding. The wider spacing of 50 cm x 40 cm reduced the competition of nutrients and other growth resources among the genotypes, thus encouraging a high number of seeds per plant. Hunter et al. (2020) reported a rise in growth components and yields with broader plant spacing in wheat. The significant landrace effect noted for number of pods per plant at Kangaru site is attributed to the adaptation of the landrace to the study site. The red-speckled landrace might have been more adaptive to the study site, thus the high pod number per plant. The significant landrace effect recorded for the number of seeds per plant and the length of seeds at Kangaru site can be attributed to good adaptation of the landrace to the study site. The red speckled landrace was well adapted to the study site among the genotypes, thus encouraging a high number of seeds on each plant and the length of the seeds. Ouedraogo et al. (2012) explained that genetic and environmental aspects affect seed weight and yields.

The significant landrace effect for 100 seed weight at Kangaru site could be attributed to good adaptation of the landrace at the site. The red-speckled landrace had more adaptive features to the study site among the genotypes, thus recording seed weight. Tehulie and Yimam (2021) reported that the high grain yields were recorded because growth factors are efficiently used under various interactions. The significant landrace effect noted for the seed yield at Kangaru site could be attributed to more adaptation of the landrace to the study site. The red speckled landrace had more adaptive features for the study site among the genotypes, thus recording the highest seed yields. Keerthi et al. (2015) indicated that the quantity of produce gathered in every unit of area for a specific period is indicated by crop yield, which is significant in agriculture. The significant spacing effect observed in the current research for the 100 seed weight at Ishiara site could be attributed to reduced interspecies competition. The wider spacing of 50 cm x 40 cm could have reduced the competition of nutrients and other growth resources among the genotypes, thus encouraging a high 100-grain weight. Saha et al. (2020) noted that chickpea plants experienced increased grain yield under extensive spacing.

The significant landrace effect on pods count and the length of pods at Ishiara site can be attributed to the adaptation of the landrace to the study site. The red-speckled landrace utilized the resources available maximum among the genotypes, thus encouraging a high quantity of pods per plant and increasing the length of pods. The significant landrace effect on the quantity and length of seeds produced at Ishiara site can be attributed to the adaptation of the landrace to the study site. The red-speckled landrace was well adapted to the study site among the genotypes, thus recording many seeds per plant and the length of seeds. Naeem et al. (2015) articulated that the genetic characteristics of the landraces may influence the disparity in the number of pods and seeds per plant.

The significant landrace effect noted for 100-grain weight at the Ishiara site could be attributed to the adaptation of the landrace to the study site. The red-speckled landrace utilized the resources available maximum among the genotypes, thus encouraging a high 100-grain weight. The significant landrace effect recorded for seed yield at Ishiara site can be attributed to the adaptation of the landrace to the study site. The red speckled landrace utilized the resources available maximum among the genotypes, thus recording a high seed yield. A report by Thilini et al. (2019) showed that seed yields are significantly altered by genetic factors of the landrace and earthing up.

The significant season effect recorded for the number of pods, length of pods, the number of seeds per plant, and the seed yields in the Ishiara site can be attributed to variations in weather conditions. Short rains of the 2019 season performed better due to favourable weather conditions like high precipitation and temperature (Appendix 2), which increased the growth components of Bambara groundnut. These variations observed in yield components of Bambara groundnuts across the seasons suggested that variations exist among Bambara groundnut landraces (Valombola et al., 2019). The significant spacing x landrace interaction effect perceived for the number of seeds per plant in Ishiara site indicates that spacing positively affected the yields of the landraces. The significant landrace effect recorded for the number of pods per plant, pod width, and length of pods at Kiamuringa site could be attributed to the adaptation of the landrace to the study site. The red-speckled landrace utilized resources available maximum among the genotypes, thus encouraging a high quantity of pods per plant, width of pods, and length of pods. The significant landrace effect witnessed in this study for the number of seeds per plant, seed width, and the length of seeds at the Kiamuringa site can be attributed to the adaptation of the landrace to the study site. The red-speckled landrace was well adapted to the study site among the genotypes, thus recording a high number of seeds per plant, width of seeds, and length of seeds. Ouedraogo et al. (2012) found that rainfall, soil composition, and temperature contributed to the variation in pod formation in Bambara groundnut.

The significant landrace effect observed in this study for 100-grain weight at Kiamuringa site could be attributed to the adaptation of the landrace to the study site. Red-speckled landrace could have utilised resources available maximum among the genotypes, thus encouraging a high 100-grain weight. Masindeni (2006) recorded that landrace effect observed among the Bambara groundnut landraces was due to variation in the sizes of the individuals in South Africa. The significant landrace effect noted for seed yield at the Kiamuringa site could be attributed to the adaptation of the landrace to the study site. The red-speckled landrace utilised resources available maximum among the genotypes, thus recording high seed yield. A report by Mukhtar (2012) indicated that potential Bambara groundnut landraces produce above 4.5-ton ha^{-1} grain yields. The significant seasonal effect on number of pods, length of pods, number of seeds per plant, 100-grain weight, and seed yields at Kiamuringa site can be attributed to variations in weather conditions. Short rains of 2019 season performed better due to favourable weather conditions, which increased the growth components of Bambara groundnuts. A study by Toungos et al. (2012) reported that high quantities of pods and seeds from sites have more nutrients. The significant landrace effect recorded for number of pods per plant, pod width, and length of pods across the sites can be attributed to the adaptation of the landrace to the study site. The red-speckled landrace could have utilised the resources available optimumly among the genotypes, thus encouraging a high quantity of pods per plant, width of pods, and length of pods. The current research reported a significant landrace effect for both the number of seeds per plant and the length of seeds across the sites, which can be attributed to the adaptation of the landrace to the study site. The red-speckled landrace was well adapted to the study sites among the genotypes, thus recording many seeds per plant and length of seeds. A study by Ansa (2016) indicated that landraces that were well adapted to the environment recorded higher yields.

The significant landrace effect observed in the current study for 100-grain weight across the sites could be attributed to the adaptation of the landrace to the study site. The red-speckled landrace utilised the resources available maximum among the genotypes, thus encouraging a high 100-grain weight. The significant landrace effect observed in this study for seed yield across the sites can be attributed to the adaptation of the landrace to the study site. The red-speckled landrace utilised the resources available maximum among the genotypes, thus recording a high seed yield. A study by Thilini et al. (2019) recorded Bambara groundnut seed yields of up to 6.8 tons ha-1 in some landraces that utilised the resources optimally. The significant season effect observed for pod quantity, length of pods, the number of seeds per plant, 100-grain weight, and seed yields across regions could be attributed weather conditions. Short rains of the 2019 season performed better owing to favourable weather which increased the growth components of Bambara groundnut. Numerous ecological elements, including light, temperature, and rainfall, may influence Bambara groundnuts' growth rate and seed yields (Hasan et al., 2019).

3.5 Conclusion

The current study concluded that spacing 1 (50 cm x 20 cm) was the optimum for the production of Bambara groundnut in the dryland regions of Embu County. The landrace BG 001 was identified as the best-yielding landrace among the three genotypes tested.

3.6 Recommendation

The study recommended spacing 1 (50 cm x 20 cm) as the optimum spacing for growing Bambara groundnuts in the study area since it gave the highest yield components of Bambara groundnuts for the three landraces (BG 001; BG 003, and BG 005). In addition, the study recommended landrace BG 001 for growing in the study areas and areas with comparable agroecological characteristics since the landrace recorded the highest yield.

CHAPTER FOUR

AGRONOMIC BENEFITS OF INTERCROPPING SORGHUM WITH BAMBARA GROUNDNUT IN EMBU COUNTY

Abstract

Bambara groundnut farmers practice either pure stand or intercropped systems. However, there is scanty information regarding the intercropping requirements of this crop, and thus, the farmers' choice for either system is driven by farmers' beliefs rather than experimentally proven reasons. This study aimed to evaluate the agronomic benefits of intercropping sorghum with Bambara groundnut in the semi-arid lands of Embu. The study was conducted in Ishiara, Kiamuringa, and the University of Embu. The experimental design used was a randomized complete block design replicated thrice. Soil analysis was performed before and after the experiments. Data on sorghum included plant height, panicle length, days to physiological maturity, total grain yield, land equivalent ratio, and 100-grain mass. Data collcted on Bambara groundnuts included: plant height, plant spread, leaf area index, number of branches per plant, weight of grains per plant, number of pods per plant, length of pods, number of seeds per pod, and total dry weight. Analysis of variance was used to analyze the agronomic data and treatment means separated using Student-Newman-Keuls at a 95% confidence level. Results showed that intercropping of Bambara groundnuts with sorghum land equivalent ratio of greater than 1had a grain yield advantage of sorghum in both seasons compared to mean yields of sole crop treatments land equivalent ratio of less than 1. Across the two seasons, the total organic carbon, nitrogen percentage, and exchangeable acidity had increased. The study concluded that intercropping Bambara groundnuts with sorghum and incorporating Bambara groundnut residues in the soil between the rows yielded 3.24 ton ha^{-1} better than planting a sole sorghum crop at 2.94 ton ha^{-1}. The study recommended that farmers in the dry lands of Embu incorporate Bambara groundnuts as an intercrop with sorghum for improved yield.

4.1 Background

Recently, there has been a declining trend in crop yields due to increasing land degradation coupled with decreasing soil fertility (Badu-Apraku & Fakorede, 2017). Climate variability directly impacts crop yields due to reduced precipitation and rising temperatures (Nhamo et al., 2019). Rural agriculture needs to maximise the efficient utilisation of natural resources and step up climate risk adaptability (Matthews & McCartney, 2018). Leguminous crops contribute to increased soil fertility due to nitrogen fixation from the atmosphere into the soil by a mutual relationship with their root nodules containing microorganisms that fix nitrogen (Mazzafera et al., 2021). In this connection, there is a need to incorporate drought-tolerant legumes such as Bambara groundnuts as an intercrop with cereals to increase crop yields, especially in dry zones with marginalized soils (Mabhaudhi et al., 2017). This intercropping strategy involves growing Bambara groundnuts and cereals together in the same field, considering spacing, crop compatibility, and resource utilisation (Sidibe et al., 2020).

Legumes like Bambara groundnuts are planted alongside cereals such as maize or sorghum, to offer several advantages, including optimised land use, enhanced soil fertility through nitrogen fixation, improved pest and disease management, and efficient resource utilization (Vanlauwe et al., 2019). Intercropping allows farmers to practice the principle of natives and diversity on their farms (Onuk et al., 2017) and to utilise their farms' production potential. By utilizing the same field for two crops simultaneously, farmers can use available space efficiently, increasing overall productivity and potentially generating more produce per unit area (Tan et al., 2020). The cereal grain protein also grows in cereal-legume intercropping methods matched to sole crop systems (Jensen et al., 2007). Intercropping cereals and legumes decreases pests and disease incidences, smothers weeds, improves soil and water conservation and resistance to the lodging of crops (Pierre et al., 2022). Intercropping of cereals and legumes could result in stabilized and improved yields as reported by Peoples et al. (2009).

Maitra et al. (2019) reported that intercropping has great potential for increasing crop yields with less environmental harm than sole crops. A report by Dauna (2013) indicated that intercropping cereals with legumes increased the production of dry matter and grain yields more than monocultures in Nigeria. In an experiment of maize intercropped with Bambara groundnuts, the maize yields were significantly increased by 108% (Lengwati et al., 2020). Chimonyo et al. (2023) indicated that intercropping cereals with legumes improved nutrient yields in environments with limited water supply. Njeru et al. (2013) observed that intercropping sorghum with soybean resulted in soil moisture conservation and improved yields. Sarkar et al. (2020) pointed out that incorporating legumes into the farm can increase moisture conservation and crop yields in India. Therefore, the benefits of intercropping cereals with legumes range from increasing moisture and efficient use of nutrients to increased food and nutritive security in communities living in semi-arid areas (Smith et al., 2017).

Due to its symbiotic relationship with rhizobium microorganisms, the legume replenishes nitrogen in the soil (Kumar et al., 2022); Bambara groundnut has been used in crop rotation and intercropping programs, especially with cereals (Scott et al., 2021). Bambara groundnut is intercropped throughout South Africa with sorghum, millet and maize (Tiroesele et al., 2019). Intercropping Bambara groundnuts with cereals provides a complementary relationship between the two crops. The enhanced soil fertility achieved through the nitrogen fixation process enriches the soil with nitrogen (Mazzafera et al., 2021). This benefits the Bambara groundnuts and the associated cereal crops, as they can access this additional nutrient (Nweke, 2020). A study by Dakora et al. (1987) reported a rise in grain yields for maize by 89% in an intercrop with groundnuts in Ghana.

Intercropping Bambara groundnut with cereals could benefit the groundnut in various ways. First, it may help manage pests and diseases (Holt et al., 2021). Some grains, such as maize, emit volatile compounds that repel pests, potentially reducing pest damage to the Bambara groundnut. Additionally, the diverse plant species in an intercropping system may disrupt the buildup of specific pests or diseases that would otherwise occur in a monoculture, contributing to overall crop health (Mohammed, 2019). With their upright growth habit, cereals can provide a trellis-like structure for the trailing Bambara groundnut vines to climb, reducing the need for additional support structures (Asiwe et al., 2020). Therefore, intercropping cereals with legumes increases crop yields, reduces pests and diseases and improves soil productiveness (Kiwia et al., 2019).

The yield benefit of intercrops is calculated using the land equivalent ratio (LER). The LER is the proportionate amount of land needed for lone crops as a unit area of the intercrop to generate a comparable crop (Yu, 2016). Studies on meta-analyses of land equivalent ratios noted greater than 1 from intercropping experiments (Martin-Guay et al., 2018). A study by Parwada and Chinyama (2021) recorded a yield advantage in intercropping experiments of cowpea and sorghum compared to their monocultures. A report by Dariush et al. (2006) reported a land equivalent ratio of 2.0 in two corn varieties intercropping experiments, which indicated yield advantage. A land equivalent ratio greater than 1.31 was realize d from intercropping peanuts with maize (Feng et al., 2021). The current study used an experimental approach to examine the benefits of intercropping Bambara groundnuts with sorghum on sorghum yields and yield components.

4.2 Materials and Methods

The experiment was conducted in three study sites described in section 3.2. Landrace BG 001 (main crop) was intercropped in all three study locations with the popular Gadam sorghum variety. The landrace Bambara groundnut was selected for its popularity among farmers because it gave high yields. Gadam sorghum variety is popular among farmers due to its early maturing and drought-tolerant traits.

The experimental design was a randomised block design with three replications. Two seasons were involved in the project, as described in Section 3.2. The treatments (T) were: T1= sorghum planted as a mono-crop at a spacing of 75 cm x 10 cm; T2 = Bambara groundnut planted as a mono-crop at a spacing of 50 cm x 20 cm; T3 = sorghum rows spaced at 75 cm x 10 cm with 2 rows of Bambara groundnut in between the sorghum rows and spaced the two groundnut rows and legume residues removed after harvest; T4= similar to T3 but with legume residues incorporated into the soil after harvest.

Data collected on sorghum was plant height, panicle length, panicle weight, total grain yield, land equivalent ratio (LER) and 1000 grain mass. The data collected on Bambara groundnut included plant height, branch number, number of pods per plant, length of pods per plant, 100 grain mass, total grain yields and LER. For Bambara groundnut, the parameters were measured as explained in section 3.2.3. The parameters for sorghum were measured as follows: plant height was assessed by calculating from the base to its highest height, including the terminal leaflet, measured using a meter rule. The length of the panicle was measured using a ruler, and an average of 10 plants was recorded. The weight of a dry panicle was taken by weighing a dried panicle to 12% moisture content, and an average of 10 plants were recorded. Total grain yield was taken by weighing dried seeds for all plants at 12% moisture content. The 100-grain mass was assessed by weighing the average weight of 100 seeds after harvest at 12% moisture content.

Land equivalent ratio (LER) is a parameter used to measure the yield benefit of intercropping compared to sole crops (Kader et al., 2022). Biabani et al. (2008) estimated the LER using the following formula.

$$\boldsymbol{LER = LER_a + LER_b = \frac{y_a}{M_a} + \frac{Y_b}{M_b}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 4.1}$$

Where Ya and Yb are the yields for each crop in intercropping, Ma and Mb are the yields for each crop in sole cropping, and $\mathrm{LER_a}$ and $\mathrm{LER_b}$ are the partial land equivalent ratios for each system. When the LER =1.0, it shows that there is no yield advantage for intercropping compared with a mean value of Ma and Mb; LER>1.0 indicates a yield advantage, and LER<1.0 designates a disadvantage for intercropping (MacLaren et al., 2023).

Before and after the experiment, soil auger was used to coolect soil samples to a soil depth of 30 cm by zigzag method per plot to evaluate the amount of nitrogen and other minerals present. Ten soil samples were taken from various sections of each treatment from a depth of 30 cm at planting time and after harvest in each season. The soil samples were bulked into three composite samples for each treatment, which were later used to determine the physio-chemical traits of the soil before planting and after harvesting. The composite samples weighed 200 grams each and were sent to Kenya Agricultural & Livestock Research Organization (National Agricultural Research Laboratories) Nairobi for analysis. The soil was analysed for bulk density, pH, magnesium, phosphorus, nitrogen, potassium and organic carbon. Mehlich Double Acid Method (Mattila & Rajala, 2022) was employed to examine the available nutrient elements: Phosphorus, Potassium, Sodium, Calcium, Magnesium and Manganese. Total nitrogen content was analysed using the Kjeldahl method (Tessier, 2018). The total organic carbon was analysed using the calorimetric method (Zhou et al., 2019). The amount of carbon was ascertained on the spectrophotometer at 600 nm (Li et al., 2018). Iron, zinc and copper were extracted with 0.1 M hydrochloric acid (Jackson et al., 2018) and determined with an atomic absorption spectrophotometer (Almeida et al., 2018). Exchangeable acidity was measured by a blank titration of 75 ml potassium solution (Shi et al., 2019).

Data was subjected to three-way ANOVA using XLSTAT version 2023 to test for variations between intercropping treatments, seasons, and sites and their interactions.

Tukey's Honestly Significant Difference (HSD) Test was used to separate treatment means at P = 0.05.

4.3 Results

4.3.1 Growth response of Bambara groundnut to intercropping with sorghum

At Kangaru site, the different intercropping treatments had a highly significant ($P<0.05$) influence on plant height, number of branches, and leaf area index (LAI) of Bambara groundnut (Table 4.1) in season 1 (2019 short rains). Treatment 2 (sole crop Bambara groundnut) recorded the highest average plant height of 26.85 cm, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 23.90 cm. Treatment 3 (intercrop and Bambara groundnut residues removed) had the minimum mean plant height of 21.85 cm. The largest number of 29 branches was noted in treatment 2 (sole crop Bambara groundnut), followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 13 branches, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) had 7 branches per plant.

Similarly, treatment 2 (sole crop Bambara groundnut) recorded the highest leaf area index (LAI) of 0.78, followed by treatments 3 (intercrop and Bambara groundnut residues removed) and 4 (intercrop and Bambara groundnut residues incorporated into the soil) with an LAI of 0.70 and 0.68 respectively (Table 4.1). A comparable tendency was witnessed in the second season (2020 long rains), where the different intercropping treatments significantly influenced plant height ($P<0.001$), number of branches ($P<0.0001$), and LAI ($P<0.01$) of Bambara groundnut. Treatment 2 (sole crop Bambara groundnut) recorded the highest average plant height of 28.85 cm, followed by treatments 4 (intercrop and Bambara groundnut residues incorporated into the soil) and 3 (intercrop and Bambara groundnut residues removed), whose average plant height was 26.82 cm and 26.7 cm, respectively. The highest average of 26 branches was recorded in treatment 2 (sole crop Bambara groundnut), followed by treatment 3 (intercrop and Bambara residues removed) and 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 9 and 8 branches, respectively. Treatment 2 (sole crop Bambara groundnut) recorded the highest leaf area index of 0.71, followed by treatment 3 (intercrop and Bambara residues removed) and 4 (intercrop and Bambara groundnut residues incorporated into the soil) with leaf area index of 0.69 and 0.65, respectively (Table 4.1).

Combined season analysis recorded a highly significant intercropping effect on plant height (P<0.004), the number of branches (P<0.0001), and LAI (P<0.001) of Bambara groundnut at Kangaru site (Table 4.1). Treatment 2 (sole crop Bambara groundnut) recorded the highest average plant height of 27.85 cm, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 25.36 cm. In comparison, treatment 3 (intercrop and Bambara groundnut residues removed) had the lowest average plant height of 24.28 cm. Treatment 2 (sole crop Bambara groundnut) obtained the highest average branch number of 28.01, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with an average branch number of 10.90, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) trailed with 7.60 branches. Treatment 2 (sole crop Bambara groundnut) recorded the biggest average LAI of 0.75, followed by treatments 3 (intercrop and Bambara groundnut residues removed) and 4 (intercrop and Bambara groundnut residues incorporated into the soil) with an average leaf area index of 0.70 and 0.67, respectively.

Seasonal variations were highly significant (P<0.0001) for plant height, number of branches, and LAI at Kangaru site (Table 4.1). The highest plant height of 27.71 cm was obtained in season 2, whereas the average plant height in season 1 was 24.64 cm. An average of 16 branches was recorded in season 1, while the average branch number in season 2 was 15. The highest average LAI of 0.72 was recorded in season 1, while the average LAI in season 2 was 0.68. The season-by-treatment interactions were significant (P<0.05) for plant height and the leaf area index (Table 4.1).

At Ishiara site, the different intercropping treatments significantly (P<0.05) influenced plant height, the number of branches, and the leaf area index (LAI) of Bambara groundnut in season 1 (Table 4.1). Treatment 2 (sole crop Bambara groundnut) recorded the greatest average plant height of 40 cm, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 30.17 cm, while the least plant height of 23.21 cm was recorded in treatment 3 (intercrop and Bambara residues removed). Treatment 2 (sole crop Bambara groundnut) noted the utmost number of branches (47), followed by treatment 3 (intercrop and Bambara residues removed) with 22 branches, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) had 19 branches per plant. Treatment 2 (sole crop Bambara) recorded the highest LAI of 0.89, while treatment 3 (intercrop and Bambara residues removed) and treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) had an LAI of 0.84 (Table 4.1).

The different intercropping treatments significantly (P<0.0001) influenced the plant height, number of branches and LAI of Bambara groundnut in season 2 (Table 4.1). Treatment 2 (sole crop Bambara groundnut) recorded the a higher plant height of 29.56 cm, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 28.60 cm, and treatment 3 (intercrop and Bambara groundnut residues removed) with 26.56 cm. Treatment 2 had the highest mean number of branches (44), followed by treatment 3 with 33 branches, while treatment 4 had an average of 16 branches per plant. Treatment 2 recorded the highest LAI of 0.87, followed by treatment 3 with 0.84, while treatment 4 trailed with a LAI of 0.78 (Table 4.1).

Combined season analysis showed a highly significant influence of intercropping on plant height (P<0.001), the number of branches (P<0.0001), and the LAI (P<0.003) of Bambara groundnut (Table 4.1). Treatment 2 (sole crop Bambara goundnut) recorded the greatest average plant height of 34.92 cm, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 29.39 cm, while treatment 3 (intercrop and Bambara groundnut residues removed) had the least average plant height of 24.89 cm. Treatment 2 (sole crop Bambara groundnut) recorded the highest average branch number of 45, followed by treatment 3 (intercrop and Bambara groundnut residues removed), with an average of 28 branches per plant, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the least with an average of 18 branches per plant. Treatment 2 (sole crop Bambara goundnut) recorded the highest average leaf area index (LAI) of 0.88, followed by treatment 3 (intercrop and Bambara groundnut residues removed) and treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with an average LAI of 0.84 and 0.81, respectively. Seasonal variations were significant (P<0.05) for plant height and the number of branches, while (<0.0001) for leaf area index at Ishiara site (Table 4.1). The highest plant height of 36.74 cm was recorded in season 1, while the average plant height in season 2 was 29.10 cm. Season 2 recorded the highest number of branches (31) compared to 29 in season 1. The highest average LAI of 0.85 and 0.79 was recorded in season 1 and season 2, respectively. Season by treatment interactions was significant (P<0.05) for plant height and the LAI (Table 4.1).

At Kiamuringa site, the different intercropping treatments presented a greatly significant (P<0.0001) influence on the height of plants, the quantity of Bambara groundnut shoots, and the LAI in season 1 (Table 4.1). Treatment 2 (sole crop Bambara goundnut) recorded the highest average plant height of 30.90 cm, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 30.03 cm, while treatment 3 (intercrop and Bambara groundnut residues removed) recorded the shortest with an average plant height of 28.40 cm. Treatment 2 (sole crop Bambara groundnut) recorded an average of 30 branches, while both treatments 3 (intercrop and Bambara groundnut residues removed) and 4 (intercrop and Bambara groundnut residues incorporated into the soil) had an average of 12 branches per plant. Treatment 2 (sole crop Bambara groundnut) recorded the highest leaf area index (LAI) of 0.87, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 0.80, while treatment 3 (intercrop and Bambara groundnut residues removed) trailed with 0.78.

Additionally, intercropping treatments significantly influenced the plant height (P<0.0001), number of branches (P<0.001), and the LAI (P<0.0001) of Bambara groundnut in season 2 (Table 4.1). Treatment 2 (sole crop Bambara groundnut) recorded the higher plant height of 29.29 cm, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 23.48 cm, while treatment 3 (intercrop and Bambara groundnut removed) had the least plant height of 23.33 cm. Treatment 2 (sole crop Bambara groundnut) documented the greatest number of 44 branches per plant, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with an average of 19 branches, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded an average of 11 branches. Treatment 2 (sole crop Bambara groundnut) recorded the highest LAI of 0.88, followed by treatment 3 (intercrop and Bambara groundnut residues removed) and 4 (intercrop and Bambara groundnut residues incorporated into the soil) with LAI of 0.80 and 0.79 respectively (Table 4.1).

Combined season analysis showed a significant ($P<0.001$) influence of the intercropping on Bambara groundnut plant height, branch count, and LAI (Table 4.1). Treatment 2 (sole crop Bambara groundnut) recorded the highest average plant height of 30.01 cm, followed by treatments 4 (intercrop and Bambara groundnut residues incorporated into the soil) and 3 (intercrop and Bambara groundnut residues removed) with average plant heights of 26.76 cm and 25.87 cm, respectively. Treatment 2 (sole crop Bambara groundnut) recorded the highest average branch number of 37, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with an average branch number of 15, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) trailed with an average of 12 branches per plant. Treatment 2 (sole crop Bambara groundnut) obtained the highest average LAI of 0.87, followed by treatment 3 (intercrop and Bambara groundnut residues removed) and 4 (intercrop and Bambara groundnut residues incorporated into the soil) with average leaf area index (LAI) of 0.800.79, respectively.

Seasonal variations were highly significant ($P<0.0001$) for plant height and branch count, while $P<0.01$) for the leaf area index at Kiamuringa site (Table 4.1). The longest plant height of 39.36 cm was obtained in season 1, whereas the average plant height in season 2 was 24.36 cm. The greatest average branch number of 25 was recorded in season 2, while the average branch number in season 1 was 18. The highest average LAI of 0.81 was recorded in season 1, while the average LAI in season 2 was 0.79. The season by treatment interactions was significant ($P<0.05$) for plant height and the leaf area index (Table 4.1).

Table 4.1: Growth response of Bambara groundnut to intercropping with sorghum

		Kangaru Site			**Ishiara site**			**Kiamuringa site**		
Season	**Intercrop Treatments**	**Plant height (cm)**	**No. of Branches**	**LAI**	**Plant height (cm)**	**No. of Branches**	**LAI**	**Plant height (cm)**	**No. of Branches**	**LAI**
Short Rains 2019	T2	26.85a	29.40a	0.78a	40.27a	46.75a	0.89a	30.90a	30.27a	0.85a
	T3	21.85b	12.82b	0.70b	23.21c	22.27b	0.84b	28.40b	11.56b	0.78b
	T4	23.90b	7.44c	0.68b	30.17b	18.98c	0.84b	30.03a	11.69b	0.80b
	P value	0.0007	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Std Error	1.981	2.313	0.017	0.010	1.702	0.020	2.165	1.465	0.001
Long Rains (2020).	T2	28.85a	26.79a	0.71a	29.56a	43.60a	0.87a	29.29a	44.48a	0.88a
	T3	26.70b	8.98b	0.69a	26.56c	32.75b	0.84a	23.33b	18.63b	0.80b
	T4	26.82b	7.75c	0.65b	28.60b	16.08c	0.78b	23.48b	11.38c	0.79b
	P value	0.0002	<0.0001	0.004	0.002	<0.0001	<0.0001	<0.0001	0.002	<0.0001
	Std Error	1.231	1.978	0.012	0.012	2.056	0.001	1.001	2.613	0.014
Combined Seasons	T2	27.85a	28.10a	0.75a	34.92a	45.18a	0.88a	30.01a	37.38a	0.87a
	T3	24.28c	10.90b	0.70b	24.89c	27.51b	0.84b	25.87b	15.01b	0.79b
	T4	25.36b	7.60b	0.67c	29.39b	17.53c	0.81c	26.76b	11.54b	0.80b
	P value	<0.004	<0.0001	0.001	0.001	<0.0001	0.003	<0.0001	<0.0001	0.001
	Std Error	1.012	1.026	0.010	0.016	3.513	1.354	2.172	2.023	1.102
Seasonal Variations	Short Rains	24.64b	16.83a	0.72a	36.74a	29.33b	0.85a	29.36a	17.84b	0.80b
	Long Rains	27.71a	14.51b	0.68b	29.10b	30.81a	0.79b	24.36b	24.83a	0.82a
	P value	0.002	<0.0001	0.004	0.002	<0.001	<0.0001	<0.0001	<0.0001	0.002
	Std Error	6.29	0.0001	0.007	5.484	0.002	0.005	0.004	4.76	0.001
S*T Interactions (P Values)		0.036*	0.943	0.052	0.019*	0.746	0.012*	0.039*	0.382	0.034*

Legend: Means followed by the same letters within the column are not significantly different based on Tukey's Honestly Significant Difference ($p<0.05$). S*T is season by treatment interactions; LAI is the Leaf Area Index. Intercrop treatment T1 is not included because it was a monocrop sorghum. Treatments T2 to T4 are as described in section 4.4

4.3.2 Yield response of Bambara groundnut to intercropping with sorghum

At Kangaru site, the different intercropping treatments significantly ($P<0.05$) influenced the number of pods on a plant, the number of seeds in each pod, and the weight of 100 seeds of Bambara groundnut in season 1 (Table 4.2). Treatment 2 (sole crop Bambara groundnut) recorded the highest ($P<0.0001$) average quantity of pods per plant with 47 pods, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 14 pods and treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 13 pods per plant. Treatment 3 recorded the highest ($P<0.02$) average number of seeds per pod with 4 seeds, followed by treatments 2 (sole crop Bambara groundnut) and 4 (intercrop and Bambara groundnut residues incorporated into the soil), each with an average of 1 seed per pod. Treatment 2 (sole crop Bambara groundnut) recorded the highest ($P<0.0001$) weight of 100 seeds, which averaged 60.18 grams, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 47.18 grams and treatment 3 (intercrop and Bambara groundnut residues removed) with 38.95 grams. In addition, intercropping treatments significantly ($P<0.05$) influenced the pod quantity per plant and the weight of 100 seeds in season 2. There was no significant ($P>0.05$) difference in the quantity of seeds in a pod among the three treatments (Table 4.2). Treatment 2 (sole crop Bambara groundnut) recorded the highest ($P<0.0001$) average quantity of pods on a plant with 41 pods, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 14 pods, while treatment 3 (intercrop and Bambara groundnut residues removed) obtained the least with 12 pods per plant. Treatment 2 (sole crop Bambara groundnut) recorded the highest weight of 100 seeds, averaging 55.64 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 45.72 grams and treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 43.71 grams.

Combined season analysis showed a highly significant ($P<0.0001$) effect of intercropping on the mass of 100 seeds and the average quantity of pods per plant of Bambara groundnut at Kangaru site (Table 4.2). Treatment 2 (sole crop Bambara groundnut) recorded an average of 44 pods per plant, followed by Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) and Treatment 3 (intercrop and Bambara groundnut residues removed) with an average of 14 and 13 pods per plant, respectively. Treatment 2 achieved the highest average weight of 100 seeds at 57.91 grams, followed by treatment 4 with 45.46 grams, while treatment 3 had the lowest weight of 100 seeds at 42.34 grams. Seasonal variations were significant (P<0.0001) for the number of pods per plant, where the highest average number of 24 pods was recorded in season 1 compared to 22 pods recorded in season 2. Season by treatment interactions was not significant (P>0.05) for all the yield components at Kangaru site (Table 4.2).

At Ishiara site, the different intercropping treatments revealed a significant (P<0.0001) influence on the pod number per plant and the weight of 100 Bambara groundnut seeds in season 1. There was no significant (P>0.05) difference in the quantity of seeds within a pod among the three treatments (Table 4.2). Treatment 2 (sole crop Bambara groundnut) recorded the greatest quantity of pods in each plant with 104 pods, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 79 pods, while treatment 4 recorded an average of 52 pods per plant. Treatment 2 (sole crop Bambara groundnut) gave a higher weight of 100 Bambara groundnut seeds, averaging 63.46 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 54.75 grams and treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil)with 47.92 grams. Additionally, intercropping treatments had a highly significant (P<0.0001) influence on the pod number per plant and the weight of 100 Bambara groundnuts in season 2 (Table 4.2). Treatment 2 (sole crop Bambara groundnut) recorded the highest pods per plant (69), followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 67 pods, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) obtained the lowest number of 27 pods per plant. Treatment 3 (intercrop and Bambara groundnut residues removed) recorded an average 100-grain weight of 61.25 grams, followed by treatment 2 (sole crop Bambara groundnut) with 59.00 grams, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) trailed with 45.98 grams.

Combined season analysis showed a significant (P<0.0001) effect of intercropping on weight of 100 seeds and average number of pods per plant of Bambara groundnut (Table 4.2). Treatment 2 (sole crop Bambara groundnut) recorded the highest average number of pods per plant with 86 pods, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with an average of 73 pods, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) had an average of 39 pods per plant. Treatment 2 (sole crop Bambara groundnut) recorded the high weight of 100 seeds, 61.46 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed), with an average of 57.00 grams, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) had the lowest average weight of 100 seeds, with 45.98 grams. Seasonal variations were significant ($P<0.0001$) for the number of pods on a plant, where the maximum number of 75 pods was documented in season 1 compared to season 2, with an average of 52 pods. Season by treatment interactions were not significant ($P>0.05$) for all the yield elements at Ishiara site (Table 4.2).

At Kiamuringa site, intercropping treatments significantly ($P<0.0001$) influenced the number of pods each plant produces and the weight of 100 Bambara groundnut seeds in season 1 (Table 4.2). Treatment 2 (sole crop Bambara groundnut) recorded the greatest average quantity of pods per plant with 53 pods, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 33 pods, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) obtained 30 pods per plant. Treatment 2 (sole crop Bambara groundnut) recorded the highest weight of 100 Bambara groundnut seeds, averaging 57.78 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 43.63 grams and treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 41.92 grams. Furthermore, intercropping treatments had a significant ($P<0.0001$) influence on how many pods are in each plant and the weight of 100 Bambara groundnut seeds in season 2 (Table 4.2). Treatment 2 (sole crop Bambara groundnut) achieved an average of 70 pods per plant, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 47 pods, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) obtained 25 pods per plant. Treatment 2 (sole crop Bambara groundnut) recorded the highest weight of 100 Bambara groundnut seeds, averaging 57.41 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 45.72 grams and treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 34.52 grams.

Combined seasons of intercropping treatments had a significant (P<0.0001) effect on the number of pods on a plant and the weight of 100 seeds of Bambara groundnut (Table 4.2). Treatment 2 (sole crop Bambara groundnut) recorded the highest average number of pods per plant with 62 pods, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with an average of 40 pods, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) had an average of 28 pods per plant. Treatment 2 (sole crop Bambara groundnut) documented the highest weight of 100 seeds, 58.10 grams, followed by treatment 3 (intercrop and Bambara grounnut residues removed), with an average of 44.68 grams, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) had the lowest average weight of 100 seeds, with 38.22 grams. Seasonal variations were significant (P<0.0001) for the number of pods in each plant, whereby an average of 76 pods was recorded in season 1 compared to an average of 52 pods recorded in season 2. Season-by-treatment interactions were significant (P<0.05) for the number of pods per plant and the average weight of 100 seeds.

Table 4.2: Yield response of Bambara groundnut to intercropping with sorghum

		Kangaru Site			Ishiara Site			Kiamuringa Site		
Season	**Intercrop Treatments**	**Pods per plant**	**Seeds per pod**	**100-grain weight (g)**	**Pods per plant**	**Seeds per pod**	**100 grain weight (g)**	**Pods per plant**	**Seeds per pod**	**100 grain weight (g)**
Short Rains 2019	T2	47.33a	1.06b	60.18a	104.02a	1.06	63.46a	53.35a	1.08	57.78a
	T3	14.17b	3.82a	38.95c	79.04b	1.00	54.75b	32.48b	1.02	43.63b
	T4	13.31b	1.04b	47.18b	51.65c	1.04	47.92c	30.08c	1.02	41.92c
	P value	<0.0001	0.02	<0.0001	<0.0001	0.238	<0.0001	<0.0001	0.489	<0.0001
	Std Error	2.165	0.014	1.587	3.129	0.183	1.587	3.023	0.014	1.587
Long Rains 2020	T2	41.29a	1.06	55.64a	68.69a	1.13	59.45a	70.42a	1.10	58.41a
	T3	12.35b	1.00	45.72b	67.29a	1.02	61.25a	46.73b	1.10	45.72b
	T4	14.44b	1.06	43.71b	27.77b	1.02	44.03b	25.17c	1.02	34.52c
	P value	<0.0001	0.489	<0.0001	<0.0001	0.489	<0.0001	<0.0001	0.181	<0.0001
	Std Error	3.554	0.324	1.745	3.087	0.298	1.587	2.143	0.218	1.121
Combined Seasons	T2	44.31a	1.06b	57.91a	86.36a	1.10	61.46a	61.89a	1.09	58.10a
	T3	13.26b	2.41a	42.34b	73.17b	1.01	57.00b	39.61b	1.06	44.68b
	T4	13.88b	1.05b	45.46b	39.71c	1.03	45.98c	27.63c	1.02	38.22c
	P value	<0.0001	0.035	<0.0001	<0.0001	0.154	<0.0001	<0.0001	0.234	<0.0001
	Std Error	2.671	0.675	1.093	3.982	0.655	1.736	3.045	0.543	1.023
Seasonal Variations	Short Rains	24a	1.04	55.04	75.17a	1.01	54.23	76.98a	1.03	53.95
	Long Rains	22b	1.05	54.91	52.87b	1.05	53.87	52.10b	1.04	52.90
	P value	<0.0001	0.218	0.944	<0.0001	0.121	0.861	<0.0001	0.325	0.831
	Std Error	2.902	0.011	1.296	2.132	0.127	1.712	2.40	0.021	1.312
S*T Interactions (P Values)		0.095	0.348	0.074	0.070	0.890	0.014	0.076	0.421	0.048

Legend: Letters 'a', 'b' and 'c' indicate statistically different means based on Honestly Significant Difference (p< 0.05). S*T is seasonal treatment interactions. Intercrop treatment T1 is not included because it was a monocrop sorghum. Treatments T2 to T4 are as described in section 4.4

4.3.3 Overall growth response of Bambara groundnut

Combined analysis of the growth and yield data obtained from all three sites over the two cropping seasons revealed a significant ($P<0.0001$) treatment effect on the overall average plant height and the average number of pods per plant while ($P<0.05$) average quantity of branches per plant, leaf area index and the average weight of 100 grains (Table 4.3). Treatment 2 (sole crop Bambara groundnut) lead in the overall plant height with 30.96 cm, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with an average overall plant height of 28.33 cm. Treatment 3 (intercrop and Bambara groundnut residues removed) recorded the shortest overall average plant height of 25.18 cm. Treatment 2 gave a higher average number of branches (37 branches), followed by treatment 3, which recorded 18 branches, while treatment 4 trailed with an average of 12 branches.

Treatment 2 (sole crop Bambara groundnut) recorded the highest average leaf area index (LAI) of 0.83, followed by treatment 3 (intercrop and Bambara groundnut residues removed), which recorded an average LAI of 0.78, while treatment 4 had the lowest LAI of 0.76. Treatment 2 (sole crop Bambara groundnut) recorded the largest average pod number per plant, with 65 pods, followed by treatment 3 (intercrop and Bambara groundnut residues removed), which recorded an average of 42 pods, while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) had the least, with an average of 27 pods per plant. Treatment 2 (sole crop Bambara groundnut) recorded the highest average weight of 100 seeds with 59.99 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed), which recorded an average weight of 100 seeds with 48.17 grams while treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) had the least, averaging 42.72 grams.

Combined analysis showed greatly significant site variations ($P<0.005$) in plant height, weight of 100 Bambara groundnut seeds, number of pods per plant, branch number, and leaf area index, as shown in Table 4.3. Ishiara site recorded a higher plant height of 32.92 cm, followed by Kiamuringa site, with an average height of 29.80 cm, while the Kangaru site obtained the least average plant height of 27.68 cm. Ishiara site recorded the highest number of branches, 30, followed by Kiamuringa site, with an average of 21 branches, while Kangaru site obtained an average of 16 branches per plant. Ishiara site recorded the highest LAI of 0.84, followed by Kiamuringa site with 0.81, while Kangaru site obtained an average LAI of 0.70. Ishiara site had the highest number of pods per plant, 66, followed by Kangaru site, with each plant producing 43 pods on average, while Kiamuringa site obtained an average of 24 pods per plant. Ishiara site recorded the highest number of 100-seed weight of 54.98 grams, followed by Kiamuringa site with an average of 48.53 grams, while Kangaru site obtained an average of 48.00 grams.

Seasonal variations were highly significant (P<0.0001) in plant height, where the highest average height of 32.20 cm was recorded in season 1 compared to season 2, where the plant height of Bambara groundnut averaged 28.06 cm. Seasonal variations were also significant (P<0.05) for pods per plant, where the highest average of 47 pods was documented in season 1, while the number of pods in season 2 was 42. Significant (P<0.05) seasonal variations were also recorded in 100 seed weight, where the high average 100 seed weight of 56.17 grams was recorded in season 1 while season 2 achieved an average seed weight of 44.56 grams. Season-by-treatment interactions were significant (P<0.05) for number of branches and 100-grain weight.

Table 4.3: Response of Bambara groundnut to intercropping across sites and seasons

Season	Intercrop Treatments	Plant height (cm)	No. of Branches	LAI	Pods per plant	Seeds per pod	100 seed weight (g)
Combined seasons	T2	30.96a	36.72a	0.83a	62.25a	1.08	59.99a
	T3	25.18c	17.67b	0.78b	36.01b	1.09	48.17b
	T4	28.33b	12.05c	0.76c	27.07c	1.03	42.72c
	P Value	<0.0001	0.022	0.006	<0.0001	0.143	0.001
	Standard Error	0.814	0.954	0.035	1.962	0.123	1.342
Site Variations	Ishiara	32.92a	30.07a	0.84a	66.41a	1.05	54.98a
	Kiamuringa	29.80b	21.33b	0.81b	23.81c	1.04	48.53b
	Kangaru	27.68c	15.70c	0.70c	43.04b	1.06	48.00b
	P value	<0.0001	<0.0001	<0.0001	<0.0001	0.274	0.005
	Standard Error	0.726	1.076	0.007	2.021	0.042	1.013
Seasonal Variations	Short Rains 2019	32.20a	21.35	0.79	47.27a	1.04	56.17a
	Long Rains 2020	28.06b	23.38	0.78	41.57b	1.06	44.56b
	P value	<0.0001	0.112	0.144	0.036	0.158	0.003
	Standard Error	0.593	0.878	0.034	1.843	0.032	1.269
St*T Interactions (P Values)		0.993	0.658	0.187	0.889	0.228	0.653
Sn*T Interactions (P Values)		0.894	0.040	0.454	0.766	0.869	0.094

Legend: Letters ‘a’, ‘b’ and ‘c’ indicate statistically different means based on Honestly Significant Difference ($p < 0.05$). St*T is site by treatment interactions; Sn*T is season by treatment interactions; LAI is the Leaf Area Index. Intercrop treatment T1 is not included because it was a monocrop of sorghum.

4.3.4 Response of sorghum to intercropping with Bambara groundnut

At Kangaru site, intercropping treatments significantly (P<0.01) influenced the height of plants while P<0.01) for panicle length and panicle weight of sorghum in season 1 (Table 4.4). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded a higher (P<0.0001) plant height of 107.97 cm, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 98.87 cm, while treatment 1 (sole crop sorghum) obtained a plant height of 91.44 cm. Treatment 4 recorded the highest (P<0.01) panicle length of 21.03 cm, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 20.79 cm, while treatment 1 (sole crop sorghum) obtained 19.64 cm. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest (P<0.01) panicle weight of 33.95 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 30.19 grams, while treatment 1 (sole crop sorghum) obtained 24.32 grams.

In the same site, the intercropping treatments significantly (P<0.05) influenced the height of plants, panicle length, and panicle weight of sorghum in season 2 (Table 4.4). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) achieved a plant height of 133.50 cm, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 127.25 cm, while Treatment 1 (sole crop sorghum) obtained a plant height of 123.92 cm. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest panicle length of 20.84 cm, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 20.79 cm, while treatment 1 (sole crop sorghum) obtained a panicle length of 19.84 cm. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest panicle weight of 36.66 grams, followed by treatment 3 with 34.54 grams, while treatment 1 (sole crop sorghum) obtained 28.24 grams (Table 4.4).

Combined season's analysis showed a significant (P<0.05) influence of the intercropping treatments on the plant height, panicle length, and panicle weight of sorghum at Kangaru site (Table 4.4). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the greatest average plant height of

120.74 cm, followed by treatment 1 (sole crop sorghum), which had an average plant height of 107.68 cm, whereas treatment 3 (intercrop and Bambara groundnut residues removed) had the shortest plant height, which averaged 113.06 cm. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest average panicle length of 20.93 cm, followed by treatment 3 (intercrop and Bambara groundnut residues removed), which had an average panicle length of 20.79 cm, while treatment 1 (sole crop sorghum) had the shortest average panicle length of 19.74 cm (Table 4.4). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest average panicle weight of 35.35 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed), which had an average panicle weight of 32.36 grams, while treatment 1 (sole crop sorghum) had the lowest average panicle weight of 26.78 grams.

Seasonal variations were significant ($P<0.05$) for the plant height, panicle length, and panicle weight of Bambara groundnut. Season 2 recorded an average plant height of 129.54 cm, significantly shorter than 98.73 cm in season 1. The sorghum plants obtained an average panicle length of 20.33 cm and 19.56 cm in seasons 2 and 1, respectively. Season 2 recorded a significantly higher panicle weight of 33.87 grams than the average panicle weight of 30.68 grams in season 1. The season-by-treatment interactions were significant ($P<0.05$) for the height of plants and the panicle weight but not significant ($P>0.05$) for panicle length of sorghum.

At Ishiara site, intercropping treatments significantly ($P<0.001$) influenced the plant height and panicle weight of sorghum in season 1. However, they had no significant ($P>0.05$) influence on the panicle length (Table 4.4). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) achieved a plant height of 148.67 cm, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 141.43 cm, while treatment 1 (sole crop sorghum) obtained an average plant height of 100.59 cm. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest panicle weight of 37.28 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 34.54 grams, while treatment 1 (sole crop sorghum) obtained an average panicle weight of 29.12 grams.

The intercropping treatments significantly (P<0.001) influenced the panicle height and panicle weight of sorghum in season 2. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest panicle height of 129.52 cm, followed by Treatment 2 with 124.25 cm, while treatment 3 (intercrop and Bambara groundnut residues removed) obtained 121.29 cm. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest panicle weight of 32.27 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 30.35 grams, while treatment 1 (sole crop sorghum) obtained 24.09 grams (Table 4.4).

Combined season analysis showed a significant (P<0.01) influence of the intercropping treatments on the height of plants and panicle weight of sorghum at the Ishiara site (Table 4.4). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the greatest average plant height of 139.11 cm, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with an average plant height of 131.36 cm, although treatment 1 (sole crop sorghum) had the lowest average plant height of 109.92 cm. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) had the highest average panicle weight of 34.87 grams, followed by treatment 3 (intercrop and Bambara residues removed), which had an average panicle weight of 32.44 grams, while treatment 1 (sole crop sorghum) had the lowest average panicle weight of 26.70 grams (Table 4.4).

Seasonal variations were significant (P<0.05) for sorghum's plant height and panicle weight. Season 1 recorded a significant (P<0.003) upper plant height of 140.99 cm compared to the average plant height of 137.32 cm obtained in season 2. Similarly, season 1 showed a significantly (P<0.008) higher panicle weight of 32.87 grams compared to the average panicle weight of 29.43 grams recorded in season 2. Season-by-treatment interactions were significant (P<0.001) for the plant height and the panicle weight but not significant (P>0.05) for the panicle length of sorghum (Table 4.4).

At Kiamuringa site, intercropping treatments significantly (P<0.01) influenced height of the plant, length of panicle, and panicle weight of sorghum in season 1 (Table 4.4).

Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the greatest plant height of 107.03 cm, followed by treatment 3 (intercrop and Bambara groundnut residues removed), with 101.12 cm, while treatment 1 (sole crop sorghum) obtained a plant height of 85.94 cm. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest panicle length of 20.91 cm, followed by treatment 3 (intercrop and Bambara groundnut residues removed), with 19.61 cm, while treatment 1 (sole crop sorghum) obtained 18.46 cm. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest panicle weight of 34.87 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 34.60 grams, while treatment 1 (sole crop sorghum) obtained 37.41 grams. In the same site, the different intercropping treatments (P<0.001) significantly influenced the panicle weight of sorghum in season 2. However, they had no significant (P>0.05) influence on the plant height and panicle length (Table 4.4). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest panicle weight of 31.69 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 28.29 grams, while treatment 1 (sole crop sorghum) obtained 24.36 grams.

Combined season analysis showed a significant (P<0.05) influence of the intercropping treatments on plant height, panicle length, and panicle weight of sorghum at Kiamuringa site (Table 4.4). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded an average plant height of 116.31 cm, followed by treatment 3 (intercrop and Bambara groundnut residues removed), which had a plant height of 111.80 cm, while treatment 1 (sole crop sorghum) had the lowermost average plant height of 103.16 cm. Treatment 4 (iintercrop and Bambara groundnut residues incorporated into the soil) recorded the highest average panicle length of 20.73 grams, followed by treatment 3 (intercrop and Bambara groundnut residues removed), which had an average panicle length of 19.56 grams, while treatment 1 (sole crop sorghum) had the shortest average panicle length of 18.82 grams (Table 4.4). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest average panicle weight of 34.78 grams, followed by treatment 3 (intercrop and Bambara groundnut residues incorporated into the soil), which had an average panicle weight of 30.45 grams, while treatment 1 (sole crop sorghum) had the lowest average panicle weight of 25.88 grams.

Seasonal variations were significant ($P<0.05$) for sorghum's plant height and panicle weight (Table 4.4). The sorghum plants recorded an average plant height of 123.91 cm and 97.54 cm in seasons 2 and 1, respectively. Season 1 recorded a significantly higher panicle weight of 31.98 grams than the average panicle weight of 29.15 grams in season 2. The season-by-treatment interactions were significant ($P<0.01$) for the average plant height, panicle length and the average panicle weight of sorghum.

Table 4.4: Growth and yield response of sorghum to intercropping with Bambara groundnut

		Kangaru Site			Ishiara site			Kiamuringa site		
Season	**Intercrop Treatments**	**Plant height (cm)**	**Panicle length (cm)**	**Panicle weight (g)**	**Plant height (cm)**	**Panicle length (cm)**	**Panicle weight (g)**	**Plant height (cm)**	**Panicle length (cm)**	**Panicle weight (g)**
Short Rains 2019	T1	91.44c	19.64c	24.32c	100.59c	19.84	29.12b	85.94b	18.46c	27.41b
	T3	98.87b	20.79b	30.19b	141.43b	20.79	34.54a	101.12a	19.61b	32.60a
	T4	107.97a	21.03a	33.95a	148.67a	21.40	37.28a	107.03a	20.91a	34.87a
	P Value	0.0001	0.001	0.002	0.001	0.200	0.001	0.0007	0.004	0.0008
	Std Error	0.543	0.407	1.098	2.019	0.287	1.532	2.648	0.395	1.034
Long Rains 2020	T1	123.92c	19.84b	28.24b	124.25c	18.95	24.09b	120.38	19.17	24.36c
	T3	127.25b	20.79a	34.54a	121.29b	20.01	30.35a	122.48	19.51	28.29b
	T4	133.50a	20.84a	36.66a	129.54a	19.90	32.27a	125.58	19.83	31.69a
	P Value	0.002	0.015	0.003	0.040	0.200	0.001	0.200	0.300	0.0002
	Std Error	0.956	0.237	1.124	2.847	0.266	1.419	2.231	1.098	1.194
Combined Seasons	T1	107.68c	19.74b	26.78c	109.92c	19.39	26.70c	103.16c	18.82c	25.88c
	T3	113.06b	20.79a	32.36b	131.36b	20.40	32.44b	111.80b	19.56b	30.45b
	T4	120.74a	20.93a	35.31a	139.11a	20.65	34.78a	116.31a	20.73a	33.28a
	P value	0.045	0.014	0.003	0.003	0.231	0.008	0.004	0.002	0.007
	Std Error	1.042	0.963	1.653	2.761	0.786	1.987	2.098	0.416	1.034
Seasonal Variations	Short Rains	98.73b	19.56b	30.68b	140.99a	20.87	32.87a	97.54b	19.54	31.98a
	Long Rains	129.54a	20.33a	33.87a	137.32b	20.38	29.43b	123.91a	19.93	29.15b
	P value	0.003	0.043	0.043	0.003	0.421	0.034	0.035	0.872	0.005
	Std Error	0.780	0.193	0.917	1.707	0.218	1.158	2.162	1.042	0.975
S*T Interactions (P Values)		0.001	0.453	0.001	0.001	0.657	0.001	0.076	0.001	0.001

Legend: Letters ‘a’, ‘b’ and ‘c’ indicate statistically different means based on Honestly Significant Difference (p< 0.05). S*T is season treatment interactions. Intercrop treatment T2 is not included because it was a monocrop of Bambara groundnut. Treatments T1, T3 and T4 are as described in section 4.4.

4.3.5 Combined intercropping effects on sorghum

Combined analysis revealed a significant ($P<0.05$) treatment effect on panicle length and panicle weight but no significant ($P>0.05$) effect on plant height (Table 4.5). Treatment 3 recorded the highest panicle length of 20.69 cm, followed by treatments 1 (sole crop sorghum) and 4 (intercrop and Bambara groundnut residues incorporated into the soil) with panicle lengths of 19.73 cm and 19.70 cm, respectively. Treatment 3 (intercrop and Bambara groundnut residues removed) recorded the highest panicle weight of 32.38 grams, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) and treatment 1 (sole crop sorghum) with panicle lengths of 29.77 grams and 29.73 grams, respectively. The combined analysis also showed significant ($P<0.05$) site disparities in height of the plant, panicle length, and panicle weight (Table 4.5). Ishiara site recorded significantly ($P<0.0001$) the highest plant height of 140.99 cm, followed by Kangaru site with an average plant height of 98.73 cm, while Kiamuringa site obtained a plant height of 96.64 cm. Ishiara site recorded the highest ($P<0.001$) average panicle length of 20.39 cm, followed by Kangaru site with 20.31 cm, and Kiamuringa site with 19.40 cm. Ishiara site recorded the highest ($P<0.02$) panicle weight of 31.95 grams, followed by Kiamuringa site with an average panicle weight of 30.89 grams. Kangaru site obtained an average panicle weight of 29.05 grams.

Seasonal variations significant ($P>0.05$) for average plant height, average panicle length and average panicle weight. Season 2 recorded a significantly higher panicle height of 128.22 cm as compared to the average panicle height of 99.43 cm recorded in season 1. Season 1 recorded a significantly higher panicle length of 20.23 cm as compared to the average panicle length of 19.88 cm recorded in season 2. Season 1 recorded a significantly higher panicle weight of 31.59 grams as compared to the average panicle weight of 30.17 grams recorded in season 2. Similarly, the site by treatment variations and the season and treatment variations were significant ($P<0.05$) for panicle length.

Table 4.5: Intercropping effects on sorghum across sites and seasons

Season	Intercrop Treatments	Plant height (cm)	Panicle length (cm)	Panicle weight (g)
Combined seasons	T1	111.81	19.73b	29.73b
	T3	111.67	20.69a	32.38a
	T4	112.87	19.70b	29.77b
	P Value	0.780	0.001	0.013
	Standard Error	0.924	0.182	0.512
Site Variations	Ishiara	140.99a	20.39a	31.95a
	Kiamuringa	96.64b	19.40b	30.89b
	Kangaru	98.73b	20.31a	29.05c
	P value	<0.0001	0.001	0.017
	Standard Error	1.307	0.423	0.685
Seasonal Variations	Short Rains 2019	99.43b	20.23a	31.59a
	Long Rains 2020	128.22a	19.88b	30.17b
	P value	0.001	0.024	0.027
	Standard Error	1.067	0.148	0.559
St*T Interactions (P Values)		0.041	0.861	0.735
Sn*T Interactions (P Values)		0.062	0.883	0.861

Legend: Letters 'a', 'b' and 'c' indicate statistically different means based on Honestly Significant Difference (p< 0.05). St*T is site and treatment interactions while Sn*T is season treatment interactions. Intercrop treatment T2 is not included because it was a monocrop of Bambara groundnut. Treatments T1= sole crop sorghum, T3= intercrop and Bambara groundnut residues removed and T4= intercrop and Bambara groundnut residues incorporated into the soil.

4.3.6 Intercrop effects on grain yields of sorghum and Bambara groundnuts

Table 4.6 presents the effect of intercropping on sorghum and Bambara groundnut yields and the land equivalent ratio (LER) across the three study sites. At Kangaru site, intercropping treatments significantly (P<0.05) influenced the total grain yields in season 1 (Table 4.6). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest (P<0.003) yields of sorghum at 3.59-ton ha^{-1}, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 3.04 ton ha^{-1}, while treatment 1 (sorghum monocrop) recorded the lowest yields of 2.53-ton ha^{-1}. On the other hand, treatment 2 (Bambara groundnut monocrop) recorded the highest (P<0.0001) Bambara groundnut yields of 2.49 tons ha^{-1}, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 1.53 tons ha^{-1}, while treatment 3 obtained 0.51 tons ha^{-1}. During the same season, treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest land equivalent ratio of 6.56, followed by treatment

3 (intercrop and Bambara groundnut residues removed) with 2.25, while monocrop treatments had a land equivalent ratio of 1.

The treatments significantly ($P<0.001$) influenced total yields of both sorghum and Bambara groundnut in season 2 (Table 4.6). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the largest sorghum yields of 3.39 ton ha^{-1}, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 3.07 ton ha^{-1}, while treatment 1 (sorghum monocrop) produced the least with 2.54 ton ha^{-1}. Treatment 2 (Bambara groundnut monocrop) recorded the highest Bambara groundnut yields of 2.49-ton ha^{-1}, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 0.92 ton ha^{-1}, while treatment 3 (intercrop and Bambara groundnut residues removed) obtained 0.51 ton ha^{-1}. In the same season, treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest land equivalent ratio of 5.27, followed by treatment 3 with 2.34 while the monocrop treatments had a land equivalent ratio of 1.

Combined season analysis showed a significant ($P<0.05$) effect of intercropping on total sorghum and Bambara groundnut yields as well as on the land equivalent ratio (Table 4.6). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest average yield of sorghum with 3.48 ton ha^{-1}, followed by treatment 3 with 3.06 ton ha$^{-1,}$ while treatment 1 had the lowest sorghum yields with 2.54 ton ha^{-1}. Treatment 2 (Bambara groundnut monocrop) had the highest average total yields in Bambara groundnuts, with 2.49 tons ha-1, followed by treatment 3 (intercrop and Bambara groundnut residues removed), which produced 1.23 tons ha-1, while treatment 3 produced the lowest yields of Bambara groundnut with 0.51 tons ha^{-1}. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded a land equivalent ratio of 5.92, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 2.29, while the monocrop treatments had a land equivalent ratio of 1. Seasonal variations were significant ($P<0.05$) for the Bambara groundnut yield, with average yields of 1.68 ton ha^{-1} and 1.29 ton ha^{-1} in season 1 and season 2, separately. Seasonal variations were also highly significant ($P<0.0001$) for the land equivalent ratio, which was higher in season 1 than in season 2. The season by treatment interactions were not significant ($P>0.05$) for all three variables (Table 4.6).

At Ishiara site, intercropping treatments significantly ($P<0.05$) influenced total yields of sorghum and Bambara groundnut, as well as land equivalent ratio in season 1 (Table 4.6). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the greatest sorghum yields of 3.74 ton ha^{-1}, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 3.26 ton ha^{-1}, while treatment 1 obtained the lowest yields with 2.76 ton ha^{-1}. Treatment 2 (Bambara groundnut monocrop) recorded the highest Bambara groundnut yields of 3.73 ton ha^{-1}, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 2.53 ton ha^{-1}, whereas treatment 3 (intercrop and Bambara groundnut residues removed) obtained 2.30 ton ha^{-1}. In the same season, treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest land equivalent ratio of 2.76, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 2.01, while the monocrop treatments had a land equivalent ratio of 1. Intercropping treatments significantly ($P<0.05$) influenced the total yields in season 2 (Table 4.6). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) obtained the highest sorghum yields of 3.48 ton ha^{-1}, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 2.92 ton ha^{-1}, while treatment 1 (sorghum monocrop) obtained the least yields with 2.31 ton ha^{-1}. Treatment 2 (Bambara groundnut monocrop) recorded the highest Bambara groundnut yields of 2.80 tons ha^{-1}, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 1.57 tons ha^{-1}, while treatment 3 (intercrop and Bambara groundnut residues removed) obtained 1.30 tons ha^{-1}. In the same season, treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest land equivalent ratio of 2.41, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 1.65, while monocrop treatments had a land equivalent ratio of 1 (Table 4.6).

Combined season analysis showed a significant ($P<0.0001$) influence on the average total sorghum yields, average total Bambara groundnut yields, and the land equivalent ratio (Table 4.6). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest average sorghum yields with 3.61 ton ha^{-1}, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 3.09 ton ha^{-1}, while treatment 1 (sorghum monocrop) had the lowest yield with 2.63 ton ha^{-1}. Treatment 2 (Bambara groundnut monocrop) recorded the highest average total yields in Bambara groundnuts with 3.27 tons ha^{-1}, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 2.05 tons ha^{-1}, while treatment 4 had the least with 1.55 tons ha^{-1}. Land equivalent ratio was also significant (<0.0001) in the combined analysis whereby both treatments 3 (intercrop and Bambara groundnut residues removed) and treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded a land equivalent ratio of 2.59 while the monocrop treatments had a land equivalent ratio of 1 (Table 4.6). Seasonal variations were significant ($P<0.05$) for the Bambara groundnut yield with an average yield of 1.74 ton ha^{-1} and 1.28 tons ha-1 being obtained in season 1 and season 2, consecutively. The season by treatment relations were not significant ($P>0.05$) for all three variables (Table 4.6).

At Kiamuringa site, intercropping treatments ($P<0.05$) significantly influenced total yields of sorghum and Bambara groundnut as well as land equivalent ratio in season 1 (Table 4.6). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the best sorghum yields of 3.72 ton ha^{-1}, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 3.09 ton ha^{-1}, while treatment 1 (sorghum monocrop) obtained the least sorghum yields with 2.74 ton ha^{-1}. Treatment 2 (Bambara groundnut monocrop) recorded the highest Bambara groundnut yields of 2.35 tons ha^{-1}, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 1.95 tons ha-1, while treatment 3 (intercrop and Bambara groundnut residues removed) obtained 1.07 tons ha^{-1}. In the same season, treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest land equivalent ratio of 3.55, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 1.92, while the monocrop treatments had a land equivalent ratio of 1 (Table 4.6). In the second season, treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the greatest sorghum yields of 3.26 ton ha^{-1}, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 3.01 ton ha^{-1}, while treatment 1 (sorghum monocrop) produced the least with 2.53 ton ha^{-1}. Treatment 2

(Bambara groundnut monocrop) recorded the highest Bambara groundnut yields of 2.76 ton ha^{-1}, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) with 1.50 ton ha^{-1}, while treatment 3 (intercrop and Bambara groundnut residues removed) obtained 1.04 ton ha^{-1}. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest land equivalent ratio of 3.27, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 1.78, while the monocrop treatments had a land equivalent ratio of 1 (Table 4.6).

Combined season treatments significantly ($P<0.0001$) influenced sorghum and Bambara groundnut yields, as well as the land equivalent ratio (Table 4.6). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded the highest ($P<0.001$) average sorghum yield with 4.49 ton ha^{-1}, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 3.05 ton ha^{-1}, while treatment 1 (sorghum monocrop) had the least yield with 2.66 ton ha^{-1}. Treatment 2 (Bambara groundnut monocrop) recorded the highest ($P<0.0001$) average total yields in Bambara groundnuts with 2.56 tons ha^{-1}, followed by treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil), which had 1.73 tons ha^{-1}, while treatment 3 (intercrop and Bambara groundnut residues removed) had the least yields with 1.06 tons ha^{-1}. Land equivalent ratio was also highly significant (<0.0001) in the combined analysis with treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded land equivalent ratio of 3.14, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 1.85 while the monocrop treatments had a land equivalent ratio of 1 (Table 4.6). Seasonal variations were significant ($P<0.05$) for Bambara groundnut yield, with an average of 1.63 ton ha^{-1} and 1.22 ton ha^{-1} being obtained in season 1 and season 2, correspondingly. The season by treatment interactions were not significant ($P>0.05$) for all the three variables (Table 4.6).

Table 4.6: Intercropping effects on grain yields of sorghum and Bambara groundnut

		Kangaru			Ishiara			Kiamuringa		
Season	**Intercrop Treatments**	**Sorghum (t/ha)**	**Bambara Groundnut (t/ha)**	**LER**	**Sorghum (t/ha)**	**Bambara Groundnut (t/ha)**	**LER**	**Sorghum (t/ha)**	**Bambara groundnut (t/ha)**	**LER**
Short Rains 2019	T1	2.53c		1.00c	2.76c		1.00c	2.74c		1.00c
	T2		2.49a	1.00c		3.73a	1.00c		2.35a	1.00c
	T3	3.04b	0.51c	2.25b	3.26b	2.30c	1.90b	3.09b	1.07c	1.92b
	T4	3.59a	1.53b	6.56a	3.74a	2.53b	2.76a	3.72a	1.95b	3.55a
	P Value	0.003	<0.0001	<0.0001	0.002	<0.0001	<0.0001	0.005	<0.0001	<0.0001
	Std Error	2.651	1.012	0.122	3.241	1.045	0.128	0.219	1.785	0.310
Long Rains 2020	T1	2.54c		1.00c	2.31b		1.00c	2.53c		1.00c
	T2		2.49a	1.00c		2.80a	1.00c		2.76a	1.00c
	T3	3.07b	0.55c	2.34b	2.92b	1.30c	1.65b	3.01b	1.04c	1.78b
	T4	3.39a	0.92b	5.27a	3.48a	1.57b	2.41a	3.26a	1.50b	3.27a
	P Value	0.001	0.001	0.001	0.007	0.001	0.006	0.007	0.001	0.001
	Std Error	1.971	2.134	0.122	2.451	1.912	0.297	0.219	1.234	0.376
Combined Seasons	T1	2.54c	-	1.00c	2.63c	-	1.00c	2.66c	-	1.00c
	T2	-	2.49a	1.00c	-	3.27a	1.00b	-	2.56a	1.00c
	T3	3.06b	0.53c	2.29b	3.09b	2.05b	2.59a	3.05b	1.06c	1.85b
	T4	3.48a	1.23b	5.92a	3.61a	1.55c	2.59a	4.49a	1.73b	3.41a
	P Value	0.002	0.001	0.001	<0.0001	<0.0001	<0.0001	0.001	<0.0001	<0.0001
	Std Error	1.423	0.732	1.021	2.134	0.572	1.561	1.123	1.176	1.452
Seasonal Variations	Short Rains 2019	2.94	1.68a	2.79a	2.97	1.74a	2.64a	3.01	1.63a	2.08
	Long Rains 2020	3.08	1.29b	2.05b	3.02	1.28b	2.15b	2.91	1.22b	2.47
	P value	0.823	0.002	0.0001	0.437	0.002	0.004	0.124	0.002	0.150
	Std Error	2.129	0.104	0.276	3.192	0.843	0.132	0.179	0.923	0.112
S*T		0.968	0.453	0.079	0.576	0.758	0.210	0.695	0.758	0.605

Legend: Letters 'a', 'b' and 'c' indicate statistically different means based on Honestly Significant Difference (p< 0.05). S*T is season treatment interactions; LER = land equivalent ratio. Intercrop treatment T2 is not included in sorghum because it was a monocrop of Bambara groundnut. Similarly, intercrop treatment T1 is not included in Bambara groundnut because it was a monocrop of sorghum

4.3.7 Overall intercropping effects on sorghum and Bambara groundnut yields

Combined analysis showed a significant ($P<0.05$) treatment influence on total sorghum yield and land equivalent ratio but no significant ($P>0.05$) effect on Bambara groundnut yields (Table 4.7). Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) had the greatest sorghum grain yield of 3.24 ton ha^{-1}, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 3.17 ton ha^{-1}, while Treatment 1 (sole crop sorghum) had 2.94 ton ha^{-1}. Treatment 4 (intercrop and Bambara groundnut residues incorporated into the soil) recorded highest land equivalent ratio (LER) of 3.38, followed by treatment 3 (intercrop and Bambara groundnut residues removed) with 2.87, while the monocrop treatments 1 (sole crop sorghum) and 2 (sole crop Bambara groundnut) had a LER of 1.00.

Combined analysis indicated highly significant ($P<0.01$) site variations in sorghum yields, Bambara groundnut yields and land equivalent ratio (Table 4.7). Ishiara site recorded the greatest sorghum yield of 7.91 ton ha-1, followed by the Kangaru site with 3.17 ton ha-1, whereas the Kiamuringa site obtained the lowermost yield of 3.08 ton ha^{-1}. Ishiara site recorded the greatest Bambara groundnut yield of 4.01 ton ha^{-1}, followed by Kiamuringa site with 2.36 ton ha^{-1}, while Kangaru site obtained the smallest yield of 1.28 ton ha^{-1}. Kangaru site recorded the highest land equivalent ratio of 3.33, followed by the Kiamuringa site with 2.10, while Ishiara site obtained a land equivalent ratio of 1.82. Seasonal variations were significant ($P<0.05$) for Bambara groundnut yields, with average yields of 2.76 ton ha^{-1} and 2.35 ton ha^{-1} being recorded in season 1 and season 2, respectively. Seasonal variations were significant ($P<0.05$) for LER, with average of 2.62 and 2.21 recorded in season 1 and season 2, separately. The site-by-treatment interactions were significant on LER. The season by treatment interactions were not significant for the yields and LER.

Table 4.7: Yield of Bambara groundnut and sorghum

Season	Intercrop Treatments	Sorghum (t/ha)	Bambara Groundnut (t/ha)	LER
Combined seasons	T1	2.94b		1.00c
	T2		2.60	1.00c
	T3	3.17a	2.58	2.87b
	T4	3.24a	2.50	3.38a
	P Value	0.008	0.928	0.001
	Standard Error	0.418	1.192	0.313
Site Variations	Ishiara	7.91a	4.01a	1.82c
	Kiamuringa	3.08b	2.36b	2.10b
	Kangaru	3.17b	1.28c	3.33a
	P value	0.002	0.001	0.001
	Standard Error	1.672	0.715	0.462
Seasonal Variations	Short Rains 2019	3.19	2.76a	2.62a
	Long Rains 2020	3.05	2.34b	2.21b
	P value	0.118	0.034	0.002
	Standard Error	1.120	0.618	0.169
St*T Interactions (P Values)		0.217	0.989	0.008
Sn*T Interactions (P Values)		0.980	0.926	0.490

Legend: Letters ‘a’, ‘b’ and ‘c’ indicate statistically different means based on HSD ($p < 0.05$). St*T is site by treatment interactions; Sn*T is season by treatment interactions; LER = land equivalent ratio. Intercrop treatment T2 is not included in sorghum because it was a monocrop of Bambara groundnut. Similarly, intercrop treatment T1 was a monocrop of sorghum.

4.3.8 Soil properties in the study sites

Table 4.8 illustrates the soil chemical and physical properties for the three study sites. The samples were taken at the start of the first season and at the completion of the second season. The soil analysis showed that there was no significant ($P>0.05$) change in the soil chemical properties during the experimental period except for Potassium and exchangeable acidity which recorded significant ($P>0.05$) increase at Ishiara and Kiamuringa sites.

Table 4.8: Effects of intercropping on soil chemical and physical properties

Site	Parameter	Start	End	T-test (P Values)
Kangaru	Soil pH	4.825	4.61	0.357
	Exch. Acidity me%	1.09	1.25	0.156
	Total Nitrogen %	0.185	0.205	0.295
	Total Org. Carbon %	2.095	2.34	0.235
	Phosphorus ppm	22.5	35	0.766
	Potassium me%	0.37	0.44	0.395
	Calcium me%	0.8	1.3	0.126
	Magnesium me%	2.445	2.525	0.758
	Manganese me%	0.81	0.705	0.789
	Copper ppm	2.065	1.53	0.077
	Iron ppm	16.95	17.45	0.951
	Zinc ppm	13.3	14.505	0.911
	Sodium me%	0.17	0.43	0.618
	Soil Texture: Sand = 40%; Clay = 25%; Silt = 6%; Classification: Sand-clay			

Site	Parameter	Start	End	T-test (P Values
Ishiara	Soil pH	6.815	6.92	0.307
	Exch. Acidity me%	0.71	0.865	0.101
	Total Nitrogen %	0.12	0.13	N/A
	Total Org. Carbon %	1.405	1.525	0.500
	Phosphorus ppm	209.5	194	0.692
	Potassium me%	0.69	1.09	**0.032***
	Calcium me%	4.4	4.3	0.795
	Magnesium me%	2.115	2.015	0.781
	Manganese me%	0.565	0.58	0.856
	Copper ppm	1.65	1.59	0.905
	Iron ppm	16.85	18.35	0.909
	Zinc ppm	3.915	3.795	0.958
	Sodium me%	0.12	0.35	0.593
	Soil Texture: Sand = 50%; Clay = 14%; Silt = 6%; Classification: Silt-loam			

Site	Parameter	Start	End	T-test (P Values
Kiamuringa	Soil pH	5.215	4.49	0.541
	Exch. Acidity me%	0.55	0.65	**<0.0001**
	Total Nitrogen %	0.12	0.125	0.874
	Total Org. Carbon %	0.94	1.105	0.303
	Phosphorus ppm	77.5	74.5	0.742
	Potassium me%	0.43	0.47	0.930
	Calcium me%	1	0.9	0.500
	Magnesium me%	1.375	0.91	0.526
	Manganese me%	0.4	0.48	0.853
	Copper ppm	2.035	1.995	0.895
	Iron ppm	22.95	17.65	0.574
	Zinc ppm	2.665	3.335	0.383
	Sodium me%	0.1	0.42	0.554
	Soil Texture: Sand = 45%; Clay = 18%; Silt = 6%; Classification: Silt-loam			

Legend: Exch = exchangeable acidity, me% = milli-equivalence in percentage, ppm = parts per million

4.4 Discussion

Intercropping legumes with cereals is widespread among resource-poor smallholder farmers facing declining soil fertility and erosion challenges. Most farmers practice improved nutrition, soil and water conservation, maximization of profits, minimization of risk in opposition to complete crop failure and enhancement of soil fertility (O'Neill & Hartmann, 2023) reported that intercropping improves yields, acts as insurance in risk management against total crop failure, helps to control weeds and ensures yield stability (Mishra et al., 2023). According to Rusinamhodzi et al. (2024), intercropping cereals with cowpeas reduces striga infestation. Legumes can rely on atmospheric nitrogen during legume-based intercropping when productivity is restricted because of biological nitrogen fixing, especially in Sub-Saharan African soils (Mugwe et al., 2011).

The significantly higher leaf area index, branch count, and plant height recorded on Bambara groundnut in the monocrop treatments across the seasons in the three study sites could be attributed to minimum interspecies competition for nutrients and other growth resources. The results were slightly higher than those recorded in the literature. The sole crop of Bambara groundnut utilized the nutrients and natural resources optimally, resulting in enhanced growth. According to Tang et al. (2022), less competition for growing resources like water and light encourages healthy plant growth, resulting in a more expansive plant canopy. Chen et al. (2023) recorded a tall plant canopy from monocropping experiments in tomato-corn intercropping experiments. A study by Tariq et al. (2022) recorded a more expansive plant canopy from intercropping experiments. Aydın et al. (2021) recorded a greater leaf area index from sole crop treatments than intercropping treatments of maize and soybean. A study by Namdari et al. (2021) on soybeans indicated a greater leaf area index from monoculture experiments. Dikr and Tadesse (2022) also recorded a bigger leaf area index from sole crop treatments when evaluating the economic feasibility of intercropping different common bean varieties with maize. Chimonyo et al. (2023) reported contrary findings that cereals in intercropping experiments dominated the legumes, hence developing higher leaf canopies than monocrop treatments.

The significant seasonal effects observed for the plant height could be attributed to variations in weather conditions. Bambara groundnut performed significantly better and recorded higher growth components in the long rain (2020) season due to favourable weather conditions, particularly enhanced relative humidity and moderate temperatures (Appendix 2). Temperature and precipitation fluctuations across seasons change plant growth patterns and resource allocation. Wanjue et al. (2023), in a study involving Bambara groundnut in different seasons, reported that plants yielded differently in other seasons of the year due to changes in weather conditions.

Season-by-treatment effect observed on the plant height and leaf area index of Bambara groundnut implied that these growth components responded differently to intercropping in different seasons. This highlights the complex interactions between management practices, seasonal changes, crop responses and resilience to climate variability. Reza et al. (2022) observed significant interactions between the season and treatment for plant height and leaf area index, suggesting that the season affected how vegetables responded to fertilizer application. A study by Alhassan et al. (2012) noted that there was low general grain yield and yield elements of intercropped Bambara groundnuts as related to mono-cropping treatments because of inter-species competition for resources both above and below ground for growing, example, light, nutrients, and water. Masvaya et al. (2017) found that legumes in sole crop experiments had higher yields than intercropped legumes.

The current research noted that sorghum plants shed light on Bambara groundnut, which had a low canopy, reducing the amount of light available for photosynthesis and leading to low productivity of Bambara groundnuts. This observation is in support with a report by Ike et al. (2013) on maize–Bambara groundnut intercrop, where sole crop treatments gave greater yields to Bambara groundnut monocultures than intercrop. A study by Molatudi and Mariga (2012) also reported that tall cereal crops receive more sunlight than legumes in intercropping experiments between cereals and legumes, hence higher productivity in cereals. Bambara groundnut intercropping experiments resulted in lower total grain yields than Bambara groundnut sole crop. Uzoma et al. (2021) recorded that legumes in intercop experiments yielded lower than their monocrop treatments. Legodi et al. (2020) reported higher growth components and higher total grain yield from sole crop experiments. Njira et al. (2021) noted that a higher yield was obtained from legume monocropping experiments in maize and cowpeas intercropping experiments.

Season-by-treatment effect observed on the Bambara groundnut pods per plant and 100-grain mass implied that performance of Bambara groundnuts was influenced by treatment and specific season in which the experiment was conducted (appendix 2). Eifediyi et al. (2020) observed that growth and yield of Bambara groundnut is affected by seasons. Temperature and precipitation (Appendix 2) varied across seasons, leading to plant growth patterns and resource allocation changes. The season-by-treatment effect observed on the Bambara groundnut pods per plant and the 100-grain mass may be due to Potassium and exchangeable acidity, which were significant at the end of the experiment (Table 4.8). The short rains of the 2020 season performed better due to favourable weather conditions like relative humidity and temperatures, which increased the growth of Bambara groundnuts.

A study by Khan et al. (2021) indicated that different seasons experience changes in weather conditions and, thus, variation in crop yields in other seasons (appendix 2). Tian et al. (2015) testified that different seasons experience variations in weather conditions and, therefore, affect the general crop yields. Karunaratne et al. (2015) recorded similar findings by recording greater yields of Bambara groundnuts in high temperatures of up to 31^{o}C in South Africa. Makanda et al. (2008) noted that weather conditions in different seasons affect the Bambara groundnut yield. Olanrewaju et al. (2021) indicated that soil factors and changes in weather conditions brought about Bambara groundnut yield variation.

The significantly higher plant height, panicle length, and panicle mass recorded on sorghum in the intercropping treatment across the seasons in the three study sites could be attributed to modifying the microclimate by providing shade and reducing soil temperature fluctuations. Bambara groundnut might have covered the soil surface, which supported retention of soil moisture. This could have created a more stable environment for sorghum, promoting better growth. This observation agreed with a report by Ren et al. (2021), where intercropped maize recorded greater height on a maize-soybean intercrop in Loess Plateau, China. A report by Nassary et al. (2019) recorded high sorghum heights in intercropping experiments with coffee and bananas. These humans enhance soil structure, water retention, and microbial activity, creating a more favourable environment for sorghum growth. A report by Traore and Zemadim

(2019) recorded greater heights from sorghum intercropping treatments due to competition for resources.

The significant treatment effect observed in the current study on sorghum panicle length could be attributed to different rooting depths of sorghum and groundnuts, resulting in the more effective utilization of available water. Sorghum has deeper roots, while Bambara groundnut has shallower roots (Marshall et al., 2024). This complementary rooting pattern reduces competition for water, allowing both plants to thrive. Konan et al. (2023) reported high cassava yield in an intercropping experiment with Bambara groundnut. Mugi-Ngenga et al. (2023) reported comparable results in intercropping corn with pigeon pea experiments in Northern Tanzania. Razafintsalama et al. (2021) noted that the legumes' high yields from intercropping experiments are due to nitrogen fixation. A study by Gerrano et al. (2021) on sorghum–legume intercropping experiments recorded higher sorghum yields obtained from Bambara groundnut's nitrogen fixation.

The significant treatment effect noted in the current study on sorghum yields could be attributed to intercropping effect (Razafintsalama et al., 2021). There was an increase in soil nutrients from intercropping treatments, resulting in greater yields (Nguyen et al., 2024). Aremu-Dele et al. (2021) recorded comparable results from intercropping cashew nuts and sorghum. Yields of maize grains rose by 340% over four consecutive cropping seasons as opposed to maize grown as a single crop in gliricidia-maize intercropping (Akinnifesi et al., 2007). Intercropped sorghum benefitted from moisture storage in the soil by the Bambara residues (Gerrano et al., 2021). Sorghum yields from intercropping experiments exceeded their monocultures (Tan et al., 2020). Jensen et al. (2020) recorded greater yields in intercropping experiments with cereals due to nitrogen fixation into the soil, water conservation, modification of microclimate in the soil and efficient consumption of resources (Jensen et al., 2020). Alhassan and Egbe (2014) reported that intercropping legume crops with cereals gave higher yields than sole crop cereal.

The significant treatment effect observed in this study on Bambara groundnut yields can be attributed to the minimal competition between the species. The sole crop, Bambara groundnuts, lessened competition for nutrients and other growth resources among the treatments, thus resulting in a high crop yield. Bambara groundnut grain yields ranged from 1.28 tons/ha to 4.02 tons/ha. The average yields of Bambara groundnut vary from 300 to 800 kg/ha but can reach 4 tons ha^{-1} (Heuze & Tran, 2013). Due to minimal inter-species competition, Konan et al. (2023) and Renwick et al. (2020) recorded greater yields from sole crop Bambara treatments. A yield boost in maize-cowpea intercropping systems was reported by Quaye et al. (2020). MacLaren et al. (2023) found that legumes in sole crop treatments gave greater yields.

The significant season effect observed in the land equivalent ratio could be attributed to better resource utilization . Intercropping treatments recorded higher land equivalent ratios of more than 2, which indicates a yield advantage over sole crop treatments. Addo-Quaye et al. (2011) documented a greater land equivalent ration in maize-soybean intercrop than in their monoculture. A study by Legodi and Ogola (2020) recorded a land equivalent ratio between 0.51 and 2.13 in an experiment of intercropping cassava with legumes. Nweke and Anene (2019) recorded a land equivalent ratio of 1.54 when intercropping Bambara groundnuts with maize crops. The significant season effect observed in the Bambara groundnut yields in combined analysis can be attributed to variations in weather conditions (Appendix 2). The significant season effect observed in the Bambara groundnut yield may be due to Potassium and exchangeable acidity, which were significant at the end of the experiment (Table 4.8). These increased nutrient availability, regulation of water in the soil and increased growth and productivity of Bambara groundnut. The short rains of the 2019 season recorded higher yields due to favourable weather conditions, such as relative humidity and temperatures, which increased the growth components of Bambara groundnuts. These variations observed in yield components of Bambara groundnuts across the seasons imply variability among the Bambara groundnut landraces (Valombola et al., 2019).

4.5 Conclusion

It was evident that intercropping Bambara groundnuts with sorghum had an advantage on sorghum yield in dry lands of Embu County. The study established that intercropping sorghum with Bambara groundnut would result in a significant sorghum yield increment compared to a monoculture system. The sorghum yield can be further increased by incorporating the groundnut residues into the soil after harvest.

4.6 Recommendation

The study recommended intercropping sorghum between two rows of Bambara groundnuts in the dry lands of Embu County and areas with similar agroecological characteristics, as this would result comparatively higher sorghum yields and higher land equivalent ratio. The study also recommends incorporation of the groundnut residues into the soil after harvest to further boost the sorghum yields and to increase the organic matter content to support the subsequent crop.

CHAPTER FIVE

WILLINGNESS OF SMALLHOLDER FARMERS TO ADOPT THE BEST AGRONOMIC PRACTICES OF BAMBARA GROUNDNUT PRODUCTION IN SEMI-ARID LANDS OF EASTERN KENYA

Abstract

Drought-tolerant crops with low demand for fertilizers, such as Bambara groundnut, have yet to be promoted well in semi-arid areas. Despite its high agronomic potential and nutritive value, Bambara groundnut is not popular in most communities in Kenya except in Western, Nyanza, and Coastal regions. The willingness of farmers to adopt the crop in dry areas of Eastern Kenya has yet to be reported. The study assessed smallholder farmers' willingness to implement the suggested agronomic techniques for producing Bambara groundnuts in Embu County's semi-arid regions. The research sites were the three sub-counties of Embu County namely Mbeere North, Mbeere South, and Embu West. A well-designed questionnaire was administered to 384 smallholder farmers who attended the Farmers' Field Schools at the three locations and was used to extract data. The current study drew the sampling units using a multistage spatially stratified random sampling design. Logistic regression, averages, and percentages were used to examine the data. The study's findings showed that 60.94% of the farmers were open to using the suggested agronomic techniques. The farmers' cropping technology, farming experience, farm size, interactions with extension agents, involvement in farmers' groups, and intercropping system all impacted their willingness to use the suggested agronomic techniques. The farmer participation approach is a creative means of reaching smallholder farmers with less well-known agricultural technologies with a sustainability track record. This is one of the smart-climate approaches to addressing local food issues. By raising awareness among farmers through appropriate extension channels, they can be encouraged to use this climate-smart technology, including growing the nutrient-dense and drought-tolerant Bambara groundnut in their arid regions. The study recommended the promotion of Bambara groundnut in dry lands of Embu County to increase its adoption, which will achieve food security and income among the smallholder farmers.

5.1 Introduction

African homegrown pulses, known as Bambara groundnuts (*Vigna subterranean* L. Verdc), are resistant to heat and drought and may grow well in marginalized soils (Chai et al., 2016). As per Temegne (2018), the crop is indigenous to Northern Cameroon and North Eastern Nigeria. Third in importance in Sub-Saharan Africa (SSA), after cowpeas and groundnuts (Adzawla et al. 2016). Bambara groundnut is a common diet in Kenya's Western, Nyanza, and coastal regions (Valerie & Luvembe, 2016). The farmers grow Bambara groundnut mainly on a small scale for subsistence use. Bambara groundnut's uptake in the other areas in Kenya is poor (Oyeyinka et al., 2017). In arid regions, Bambara groundnut hold great potential for enhancing food and nutritional security. Greater awareness of the crop and its nutritional value is needed (Ogwu et al., 2018). According to Nyasimi et al. (2017), the effective uptake of new sustainable technologies in agriculture largely depends on the information dissemination channels employed. This study, therefore, used the farmer participatory approach to introduce and promote Bambara groundnut production in dry lands of Embu County. This approach enabled the participants to make well-versed choices when adopting the crop.

There is a need to adopt the best agronomic practices for Bambara groundnut in the dryer parts of Embu County, Kenya, since the crop is less known in the region (Obura, 2021). This investigation hypothesised that farmers’ participation would greatly influence their willingness to adopt the best agronomic practices on Bambara groundnut in the agronomic evaluation and their socio-economic characteristics. Large-scale farmers are risk-takers since they can put their land portions to trial (Varble et al. 2016). Researchers and extension agents are critical in adopting new agriculture technologies (Chandio & Yuansheng, 2018). The delayed adoption tendency has also been exacerbated by the fact that the target farmers and change agents have little interaction. Farmers with a close relationship with the change agent consistently adopt technology faster (Tey et al., 2017). Farmer field school (FFS) is an extension teaching approach that goes beyond disseminating technical information to farmers. The farmer field school is a participatory method where farmers learn, impart practical skills, and empower themselves (Okeoghene, 2020). Farmers participating in extension programs are better prepared to make decisions because they can weigh the projects' usefulness and complexity (Suvedi et al. 2017). Farmers can attain high and inexpensive output because the farmer-participatory approach directly addresses their demands (Lailogo et al., 2018; Bhutto et al., 2018) since the adoption rate has improved.

Carl Rogers' "adoption of innovation theory" laid this investigation's foundation (Oyeyinka et al. 2017). According to the theory, adoption is the decision to implement an invention as the best course of action. Diffusion occurs when individuals adopt new technology, products, or ideas. Barrett et al. (2020) define diffusion as a process that includes innovation, communication channels, and adoption. There are two communication channels; the first is localized, where communication is from local leaders and receivers of the same social system. Examples of this type of channel are interpersonal channels. At the same time, the second one is a cosmopolite channel, where the sender of information is from the outside social system, e.g., mass media. Another key adoption component is the social system, a set of correlated components involved in combined problem-solving to achieve a collective objective (Al-Razgan et al., 2021).

Qazi et al. (2018) cited that the innovation-decision process is an insight-finding and knowledge-refining action in which a person is encouraged to increase confidence in the advantages and shortcomings of an invention. This process has five steps, i.e., knowledge, persuasion, decision, implementation, and confirmation (Sanguinetti et al., 2018). The interpersonal channels play a major role in the knowledge stage while localize channels are more significant at the persuading stage of the innovation-decision process (Ng, 2020). The degree of adoption of technology is greatly affected by the relative advantage of innovation, observability, trial-ability, complexity, and compatibility (Qazi et al., 2018). The recommended agronomic practices are optimum spacing and intercropping sorghum with Bambara groundnut. Different farmers in different places have reportedly used varying spacing when planting Bambara groundnuts (Egbe, 2016). Bambara groundnuts have been overlooked by most farmers who intercrop with legumes, including beans, peas, and other crops (Oyeyinka et al., 2017). Therefore, this study aimed to determine how eager the farmers were to implement the most effective agronomic techniques for producing Bambara groundnuts.

5.2 Methodology

The three sites, as defined in Section 3.1, were used to make the sample data. The current study drew the sampling units using a multistage spatially stratified random sampling design. Embu County has five Sub-Counties, three of which were selected purposefully: Embu West, Mbeere North and Mbeere South Sub-County. There are seven wards in each sub-county. Sampling was done in seven Wards per Sub-County. The respondents were those farmers who attended the farmer's field schools at the end of experiment. The sample size was calculated using the following formula by Cochran (2007).

$$\mathbf{n} = \frac{\mathbf{Z^2pq}}{\mathbf{d^2}}$$ …………………..…………………….…..Equation 5.1

Where: p = estimated proportion of the target population that has the characteristics being measured (0.5), d = level of significance (0.05), q = estimated proportion of the target population that does not have the characteristics being measured (0.5), Z = the standard normal deviate at 95 per cent (1.96) confidence level, and n = the desired sample size.

$n = (1.96)^2 (0.5) (0.5) / (0.05)^2 = 384$ households.

The 384 small-scale farmers were distributed in the three Counties depending on their population through probability proportionate to size. The sampled farmers from the three sites were organised in a farmers’ field school. They were trained on Bambara groundnut's best agronomic practices and involved in agronomic data collection. This enabled them to make an informed decision on adoption. The study embraced the theory of innovation-decision model as described in section 2.7 but covered up to the decision-making stage. After the experiment, an adoption survey was carried out to determine the farmers' inclination to embrace the production of Bambara groundnut using the best agronomic practices. The data collected were the socio-economic factors that might influence the willingness of the farmers to adopt the suggested agronomic practices of Bambara groundnut. A well-structured questionnaire (Appendix 1) was used to gather data from the 384 farmers. Three farmers who were not present for the final interviews were used to pre-test the questionnaire before final data collection.

5.3 Data analysis

The socioeconomic traits of smallholder farmers employed in this research were analysed using inferential and descriptive statistics, which include means, frequencies, and percentages. The statistical package for social sciences (SPSS, version 21) was used for data analysis. The Probit model was utilized to investigate the factors influencing the farmers' willingness to adopt the best agronomic practices of Bambara groundnut. The contingent valuation method (Woo et al., 2019) was used to quantify the farmers’ willingness to adopt the best agronomic practices in producing Bambara groundnuts.

A probit model is used to explain a dichotomous variable. The variable has empirical specification framed about the latent response variable, called Y*. This variable represents the contingent willingness to adopt the best agronomic practices of Bambara groundnuts. This is explained by the equation Vanslembrouck et al. (2002) adopted.

$$\boldsymbol{y_i = \beta 0 + \sum_{k=1}^{k} \beta_{ki} x_{ki} + \varepsilon_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ Equation 5.2}$$

Where;

i stands for respondent

$X_{ki:}$ k=1 through k independent variable explaining the phenomenon for the respondent i

β_k: is the parameter that indicates the effect of X_k on y*

β_0: intercept that indicates the expected value of y*when all X_k=0

$\varepsilon_{i\,:}$ stochastic error term for respondent i

The latent variable $y_i{}^*$ is continuous, unobserved and ranges from $-\infty$ to $+\infty$

The variable $y_i{}^*$ generates the observed binary variable;

$$y_i = \begin{cases} \boldsymbol{1\ if\ yi * > 0,} \\ \boldsymbol{0\ \ otherwise.} \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Equation 5.3}$$

Dealing with willingness to adopt the best agronomic practices of Bambara groundnut production equation 5.3……is interpreted as

$$y_i = \begin{cases} 1\ if\ the\ farmer\ is\ willing\ to\ adopt \\ 0\ \ if\ the\ farmer\ is\ not\ willing\ to\ adopt \end{cases}$$

The data was then tested for multicollinearity and heteroscedasticity. The variables used in modelling factors affecting farmers' willingness to adopt the recommended agronomic practices of Bambara groundnut production (Optimum spacing and intercropping with cereals) yielded a mean Variance Inflation Factor (VIF) of 2.020. Each variable had a VIF value of less than 10 but greater than 1. According to Gujarati and Porter (2003), VIF values less than 10 show the non-existence of a multicollinearity problem.

5.4 Results

5.4.1 Farmer characteristics with categorical variables

Table 5.1 shows the results of the farmers' characteristics with categorical variables. Findings on farmer characteristics on categorical variables showed that out of the 384 farmers who participated in the investigation, 57.8% were female, whereas 42.2%

were male. The majority (57.81%) had attained a secondary level in education, out of which 20.57% had progressed to the tertiary level. Most (66.67%) of the farmers had previously adopted agricultural technologies, and 70.83% were organized into various farmer groups. All the farmers were accessing extension services, but in multiple frequencies, 22.40% received monthly services, 32.29% received the services yearly, and 45.31% received irregular services. Consequently, the farmers practised irregular cropping systems, with most (49%) practising crop rotation, whereas 21%, 13%, 9%, and 6% practised mixed cropping, intercropping, mono-cropping and multiple cropping systems. Most (58.07%) of the farmers interviewed preferred the system where cereals and Bambara groundnut were interplanted and their residues incorporated into the soil. However, 31.25% of the farmers were not impressed by the intercropping system. Eventually, 60.94% of the participants were willing to adopt the best agronomic practices of Bambara groundnuts, comprising 47% males and 53% females.

Table 5.1: Farmer characteristics with categorical variables

Characteristics	Description	Frequency	%
Gender	Male	162	42.19
	Female	222	57.81
Education level	Primary	42.19	21.61
	Secondary	222	57.81
	Tertiary	79	20.57
Previous technology adoption	No	128	33.33
	Yes	256	66.67
Farmers’ groups	No	112	29.17
	Yes	272	70.83
Extension services	Monthly	86	22.4
	Once a year	124	32.29
	Irregularly	174	45.31
Cropping system	Crop rotation	189	49.22
	Mono-cropping	36	9.38
	Intercropping	53	13.8
	Mixed cropping	81	21.09
	Multiple cropping	25	6.51
Intercropping system preferred	Groundnut residues removed	41	10.68
	Groundnut residues incorporated	223	58.07
	None	120	31.25
Willingness to adopt Bambara groundnut	Willing	234	60.94
	Not Willing	150	39.06

5.4.2 Farmer Characteristics

The continuous variables of the farmer characteristics are shown in Table 5.2. The farmers who participated in the study's interviews had an average age of 43.78 years and a farming experience of 14 years. The average household size was 5 members, and the average number of adults was 3 members per household. Generally, most farmers had small parcels of land averaging 2.33 acres, and the average farmers' farm income was KSh 46,130.21 p.a. (1 KSh = $ 0.01).

Table 5.2: Selected significant farmers' characteristics

Continuous variables	Minimum	Maximum	Mean	SD*
Farmer's Age	24	64	43.78	13.20
Farming Experience	2	35	14.07	10.65
Household size	1	8	5.42	2.01
Number of adults	1	7	3.37	1.76
Size of land	0.5	9	2.32	2.32
Farm income	20,000	95,000	46,130.21	21,214.16

**SD = Standard Deviation*

5.4.3 Willingness of the farmers to adopt Bambara groundnut

The contingent valuation method was used to quantify the farmers' willingness to adopt Bambara groundnut production. Table 5.3 shows the frequency and percentages of the farmers' willingness to adopt Bambara groundnut production. Of the 384 farmers who participated in the research, 60.94 % were willing to adopt the best agronomic practices of Bambara groundnut production. Those farmers who had attained an ordinary level of education (13.67) were more willing to adopt the agronomic practices of Bambara groundnut production. Farmers who previously adopted agricultural technology (66.67 %) were more willing to adopt the agronomic practices of Bambara groundnut. Farmers who practised different cropping systems (57.7%) were more willing to embrace the Bambara groundnut agronomic production practices Table 5.3).

5.4.4 Assessment of farmers' willingness

Most (58.07%) of the farmers interviewed preferred the system where cereals and Bambara groundnuts were interplanted and their residues incorporated into the soil.

However, 31.25% of the farmers were not impressed by any intercropping systems (Table 5.3). Eventually, 60.94% of the participants, comprising 47% males and 53% females, were willing to adopt the best agronomic practices of Bambara groundnut production.

Table 5.3: Influence of selected categorical farmer characteristics on willingness to adopt Bambara groundnut production

		Proportion (%) of Participants		
Variable		**Willing to adopt (N=234)**	**Not willing to adopt (N=150)**	***Chi***
Gender	Male	59.88	39.51	
	Female	58.4	41.6	
Education level (years)		13.67	11.22	0.051**
Previous adoption of technology (Yes)		66.67	33.33	0.069**
Farmers' groups (yes)		70.83	29.17	0.044**
Extension services (yes)		59	41	0.078**
Different cropping system (Yes)		57.7	42.3	-1.049
Intercropping cereals with Bambara groundnut residues incorporated		58.07	10.68	0.002***

***= significant at 1% and **=significant at 5%

5.4.5 Socio-economic factors influencing farmers' willingness to adopt Bambara groundnut

Table 5.4 shows probit regression model results of factors influencing farmers' willingness to adopt Bambara groundnut production. The probit model has binary dependent variables (1 = willing to adopt best agronomic practices of Bambara groundnuts; 0 = not willing to adopt best agronomic practices of Bambara groundnuts). To make it easier to comprehend significant factors, post-estimation of the selection equation verdicts was carried out to ascertain the marginal impacts. This is mainly due to coefficients consisting of values that optimize the probability distribution.

Table 5.4: Factors influencing farmers' willingness to adopt Bambara groundnut production

Variable	**Marginal effects**	**Standard Error**	**Z Score**	**P-value**
Age of the farmer	-0.0887	0.0825	-1.08	0.282
Gender of household head	0.3848	0.2190	1.76	0.079
Education level of the farmer	0.0943	0.1142	0.08	0.934
Farming experience	0.4414	0.2049	2.15	0.031**
Household size	0.4118	0.4173	-0.99	0.324
Source of labour	0.5326	0.3343	1.59	0.111
Household land size (acres)	0.5667	0.2151	2.63	0.008***
Access to extension services	0.2287	0.8242	2.77	0.006***
Membership in farmers groups	0.4648	0.1597	2.91	0.004***
Type of cropping system	-0.1948	0.6789	-2.87	0.004***
Household income	0.0001	0.0001	1.87	0.061
Off-farm income	-0.2260	0.1419	-1.59	0.111
Access to credits	0.5844	0.1074	-0.54	0.586
Previous adoption of technology	0.2660	0.5025	5.30	0.000***
Irrigation method	0.5949	0.3420	1.74	0.082
Time of planting	-0.7502	0.2665	-2.81	0.664
Intercropping system preference	0.0953	0.2196	0.43	0.048**

The values in bold were significant at ***1% and **5%; Prob > chi (1) = 0.0000; R-squared = 60.43

5.5 Discussion

Farming experience had a significant influence on farmers' willingness to adopt Bambara groundnut production. Farmers transition from traditional to modern agricultural practices as they gain expertise (Paustian & Theuvsen, 2017). The willingness of the farmers to adopt a new farming technology depends on it's superiority. Barnes et al. (2019) state that the adoption rate rises as farmers' experience levels increase. The farm's size positively affected farmers' willingness to adopt the Bambara groundnut production. This means that farmers are willing to adopt Bambara groundnut production when the size increases by a unit. Consistent results were recorded by Ntshangase et al. (2018), who found that growers with greater parcels have higher chances of adopting new agricultural technologies than those with small parcels of land.

Extension services access had a significant influence on the willingness of the farmers to adopt the best agronomic methods for Bambara groundnuts. Regular access to extension services by the farmers enhanced their willingness to adopt Bambara groundnut production. The farmers trust the known extension agents to promote new technologies; hence, farmers' decisions make them more likely to adopt new technologies. This underpins the importance of change agents when promoting the uptake of new ideas in agriculture. Suvedi et al. (2017) found that increasing farmer-extension contacts enhanced farmers' education and adoption of agricultural technologies. Membership in various farmers' groups had a positive marginal effect on the willingness of the farmers to adopt the best agronomic practices of Bambara groundnut production. Group membership provides a chance for farmers to learn from peers. This indicated that the group membership may influence the willingness of the farmer to adopt a new technology. A similar observation was made by Mango et al. (2017). Previous adoption of various cropping technologies was also found to significantly affect the willingness of the farmer to adopt Bambara groundnut production. Therefore, farmers who had previously adopted other cropping technologies were more willing to adopt Bambara groundnut production than those who had not previously adopted any technology. Singh et al. (2016) termed such early adopters of new agricultural technologies as risk takers.

Based on gender, this study found that the male participants were slightly more willing to adopt the best agronomic practices of Bambara groundnuts than their female counterparts. This was in contrast to the investigation by Rola-Rubzen et al. (2020), who informed that more men adopt technologies in agriculture than women. Verkaart et al. (2019) recorded that for a technology to be adopted widely, it must be environmentally sustainable and have more economic benefits than conventional methods.

5.6 Conclusion

The current study concluded that most farmers were willing to adopt the optimal agronomic methods for producing Bambara groundnuts. By raising awareness among farmers through appropriate extension channels, farmers can be encouraged to use climate-smart technology, including growing the nutrient-dense and drought-tolerant Bambara groundnut in arid regions.

5.7 Recommendations

The study recommended that policy interventions should target the training of farmers and the promotion of best agronomic practices of Bambara groundnut production as a drought intervention mechanism to promote food safety, particularly in dry areas of Embu County. Additionally, the Ministry of Agriculture could focus on increasing the frequency of contact between agricultural extension personnel and farmers since this will inform farmers on current farming technologies and innovations. Further assessment of the role of government policies and support mechanisms in promoting the adoption of Bambara groundnuts could be done.

CHAPTER SIX

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 Effect of different spacing on growth and yield of Bambara groundnuts

The significant spacing effect for plant spread, the overall grain yield, the number of seeds per plant, and the weight of each seed can be attributed to maximum light penetration. Greater distances between plants guarantee improved light penetration into each plant's canopy (Xin et al., 2020). Plant productivity as a whole and photosynthesis depend on light. Plants can generate more energy and use resources more effectively for growth and spread when they are spaced widely apart and receive enough light. This is in line with the study by Nderi (2020), which recorded increased plant spread intercrop spacing. It is crucial to use appropriate plant spacing to improve cotton's canopy photosynthetic capability and optimize canopy light dispersion (Chapepa et al., 2020). Haque and Sakimin (2022) concluded that wider distance between plants improved growth because there was less competition for water, nutrients, and space. A study by Zhang et al. (2021) recorded a general tendency showing cotton crops with dense populations yielded higher yields than those with sparse populations. Tehulie and Yimam (2021) reported high chickpeas yields with optimum density due to growth factors being efficiently used under varied interactions.

The significant landrace effect perceived in this study for plant spread, height, number of branches, length of seeds, number of pods per plant, yields from seeds, length and width of pods, and number of seeds per plant, 100 seed weight and total yields can be attributed to the potentially advantageous agronomic characteristics like early vigour, abundant branching, effective canopy development, and ideal plant architecture for light interception. Plants with these traits will be taller, more widely distributed, and have more branches because they maximise photosynthesis and overall plant productivity (Jia & Wang, 2021). When plants optimally utilize space, nutrients, and light, they exhibit taller canopy height and higher yields (Boateng, 2021). Seasons offer varying climatic conditions for the growth and development of various types; as a result, they can convert inputs into outputs in the form of yields (Sellami et al., 2021). Yadav et al. (2020) noted that more yields are obtained from landraces that interact synergetically with the unique environmental circumstances present in the study sites, promoting growth and development. Crop yield indicates how much produce is gathered per unit area for a certain amount of time, which is important information in agriculture (Keerthi et al., 2015). Gupta et al. (2020) noted that different crop landraces respond differently to growth conditions, thus resulting in variation in crop yield variations. Hou et al. (2020) recorded that farmers can increase maize planting density while lessening the negative environmental effects of intensive agriculture; the total amount of maize produced from the same planted area grows significantly.

The significant site effect observed in this study for plant pod width, pod number, seed length, 100 seed weight, seed yields, plant height, plant spread and the number of branches can be attributed to the variation in soil types and microclimate. The growth and production of plants can be greatly impacted by variations in soil type, fertility, pH, and nutrient availability at the sites. Plant height, spread, and branch count can vary depending on the characteristics of the soil, which also affects root development, nutrient uptake, and water retention. Garland et al. (2021) recorded a disparity in crop yields due to changes in weather factors. Liliane and Charles (2020) found that the locally obtained crop landraces yield more because they adapt well to environmental conditions. The significant season effect observed in this study for plant height, the number of branches and plant spread can be attributed to the variation in weather conditions. Ainsworth and Long (2021) noted that different seasons provide different growth conditions, thus influencing crop yield. The significant season effect pointed out in this investigation for yield components is attributable to variations in weather conditions. Dubey et al. (2020) found different wheat yields owing to changes in conditions for growth, such as temperature and moisture in the soil. Tamiru et al. (2020) indicated that higher grain yield was obtained when the conditions like rainfall and temperature were favourable in chickpeas.

6.2 Effect of intercropping Bambara groundnuts and sorghum

The significant treatment effect observed in this study for Seeds in each pod, pods per plant, plant height, number of branches, leaf area index, 100 grain mass, and total grain yield of Bambara groundnuts can be mainly ascribed to the efficient resource use, and microclimate alterations. In a sole cropping environment, where it can more efficiently exploit available resources without competition from other crops, these characteristics affect the capacity to acquire resources, grow optimally, and reach better yields. Njira et al. (2021) recorded more yield in cowpea sole crop experiment in an intercropping experiment with maize in Malawi. Nweke and Anene (2019) recorded high growth components and yields from sole crop Bambara in an intercropping experiment with maize. Ndjadi et al. (2022) recorded a greater yield from peanut monocultures in an intercropping experiment with onions in Eastern Congo. Similar findings were recorded by Kaluba et al. (2022) on sole crop legumes in an intercropping experiment with cassava. MacLaren et al. (2023) obtained greater yields from sole crop legumes in intercropping experiments with cereals in Nigeria. Ray et al. (2019) noted that variations in weather conditions significantly influence crop yield. In moderate densities, sole crop legumes recorded higher yields as compared to intercrop experiments of legumes with maize due to reduced interspecies competition (Wang et al., 2021).

The significant treatment effect observed in this study for total land equivalent ratio sites is accredited to enhance soil structure, level of organic matter, and microbial diversity, all contributing to improved soil health. Intercropping treatments recorded land equivalent ratio of more than 2. T3 (intercrop with Bambara groundnut residues removed) recorded land equivalent ratio of 1.92 and T4 (intercrop with Bambara groundnut residues added into the soil) recorded land equivalent ratio of 3.55), which indicates a yield advantage. Parwada and Chinyama (2021) conducted research that recorded land equivalent ratio greater than 1 in the cowpea- sorghum relay intercrop experiment, which designated yield benefit in the intercropping experiment due to nitrogen fixation by the legume. The significant treatment effect observed in this study for plant height, length of panicles, weight of panicles, and total production of grains for sorghum could be attributed to the complementarity of resources, nitrogen fixation, microclimate alteration, enhanced soil health, and possible economic gains. This finding aligns with a report by Audu et al. (2021) on an intercropping experiment involving maize and groundnuts, which demonstrated increased yields of maize in the intercropped plots related to sole cropping. This could be credited to nitrogen fixation by the legume intercrop Bambara groundnut remains (Dang et al., 2020). Anas et al. (2020) recorded that crop yields increased when nitrogen fixation in the soil. Legodi et al. (2020) recorded high yields of 31.1 ton ha^{-1} from cassava in an intercropping experiment with legumes.

The significant season effect observed in this study for total grain yield, plant height, and leaf area index for Bambara groundnut can be attributed to the variation in weather conditions (Appendix 2). Hussain et al. (2020) recorded that changes in weather conditions affect plant growth and the general crop yield. This aligns with Vogel et al. (2020), where crop yield varied in different seasons. Liliane and Charles (2020) noted that seasons significantly influence crop yields. The significant site effect observed in this study for height of plant, length of panicle, and weight of panicle for sorghum in combined analysis could be attributed to the variation in growth requirements in the three sites. A study by Beillouin et al. (2020) recorded that crops yield more when favourable growth conditions.

The significant site effect observed in this study for plant height, branch count, leaf area index, quantity of pods produced by each plant, seeds per pod and 100-grain mass in combined analysis can be attributed to suitable growth conditions in the study area like precipitation and temperature (Appendix 2). Mazur et al. (2019) recorded different yields on white lupine experiments in other sites. Ortiz-Bobea et al. (2021) noted that changing weather conditions significantly influences crop growth and crop yields. The significant treatment effect observed in this study for plant height, panicle length and panicle weight for sorghum can be attributed to intercropping with Bambara groundnut. Sorghum in intercropping treatments benefited from nitrogen fixation by Bambara groundnut and moisture conservation, hence increased yields. Bambara groundnut residues incorporated into the soil conserved moisture content in intercropping experiments and increased nitrates in the soil (Panagea et al., 2021).

6.3 Willingness to adopt Bambara groundnuts agronomic practices

Cropping systems have a major impact on the farmers' readiness to implement the suggested agronomic practices of Bamabara groundnut such as optimum spacing and intercropping with cereals. This implied that when farmers used a variety of cropping systems, their willingness to use Bambara groundnut optimal agronomic methods increased. These Bambara groundnut agronomic practices include optimum spacing for Bambara groundnuts and intercropping Bambara groundnuts with sorghum. Creissen et al. (2021) recorded many farmers seeking information on various cropping systems to be willing to implement fresh agricultural innovations. Most farmers preferred an intercropping system of cereals with legume residues incorporated into the soil. A study by Kebede (2020) found that most farmers preferred to include legumes as intercrops with cereals as it resulted in high yields.

Extension services access significantly affected the farmers' readiness to implement the best Bambara groundnut agronomic techniques. Regular access to extension services increased farmers' desire to start producing Bambara groundnuts. Agriculture extension workers have promoted farmers' willingness to adopt agricultural technologies. Farmers' adoption rate of climate-smart agriculture is significantly impacted by how frequently they use agricultural extension services (Zakaria et al., 2020). Group membership significantly affected the farmers' likelihood of adopting the best Bambara groundnut agronomic production methods. With more farmers participating in the group, they were more willing to implement the optimal agronomic methods for Bambara groundnuts. Musyoka et al. (2020) recorded that when farmers are members of farmers’ groups, it positively influences their adoption rate of mangoes farm level value addition technologies.

Farming experience significantly affected the farmers’ willingness to adopt Bambara groundnut production. A farmer's likelihood of adopting Bambara groundnuts rises with their level of farming experience. When farmers adopt new technologies, they switch from the old to new technologies, positively influencing greater farming experience (Acevedo et al., 2020). Ayenew et al. (2020) established that farmers’ adoption of new technology increases with an increase in farmers’ experience. The farm size notably impacted farmers' willingness to adopt the Bambara groundnut production. This indicated that expanding the farm's area by a unit resulted in farmers’ willingness to adopt Bambara groundnut production. Adams et al. (2018) found that farmers with large parcels of land have higher chances of adopting new agricultural technologies than those with small parcels.

6.4 General conclusion

1. The current study established that the yields (8.14 ton ha^{-1}) of Bambara groundnuts can be increased by optimising plant spacing, thus highlighting the need to adjust crop spacing based on crop type and environmental factors. The study further highlighted the variability among different landraces in terms of their yielding potential under different agroecological conditions, thus concluding that the choice of landrace may have a major impact on productivity. To maximise productivity and make well-informed choices about crop selection, farmers should consider the performance traits of various landraces.
2. The study also demonstrated that intercropping Bambara groundnut with sorghum yields (3.24 ton ha^{-1}) an overall yield advantage compared to mono-crop sorghum. This benefit was accredited to the capability of Bambara groundnut to fix atmospheric nitrogen in the soil, thus improving soil fertility. The crop also acted as a cover crop, conserving the available soil moisture for the benefit of both crops.
3. Finally, the study established that the farmers (60.94 %) in the target areas were willing to produce Bambara groundnuts using the best agronomic practices. Farming experience, household farm size, interaction with extension, involvement in farmers' groups, and the type of cropping system used by the farmer were some of the key factors influencing the farmers' readiness to adopt practices that maximise legume production.

6.5 General Recommendations

i) The study recommended a spacing of 50 cm x 20 cm as the optimum for producing Bambara groundnut in the dryland areas of Embu County.

ii) The study recommended intercropping sorghum between two rows of Bambara groundnuts to increase sorghum yields.

iii) Raising farmers’ awareness through appropriate extension methods can encourage farmers to start producing Bambara groundnuts in arid regions. To increase food security, particularly in semi-arid areas, policy interventions should focus on farmer training and the promotion of optimum agronomic techniques for producing Bambara groundnuts as a mechanism for drought intervention.

iv) Since Bambara groundnut yields may vary considerably among landraces, seasons, and sites, further research with more landraces in other target areas is recommended.

REFERENCES

Acevedo, M., Pixley, K., Zinyengere, N., Meng, S., Tufan, H., Cichy, K., ... & Porciello, J. (2020). A scoping review of adopting climate-resilient crops by small-scale producers in low-and middle-income countries. *Nature Plants, 6*(10), 1231-1241.

Adams, A., Jumpah, E. T., & Caesar, L. D. (2021). The nexuses between technology adoption and socioeconomic changes among farmers in Ghana. *Technological Forecasting and Social Change*, *173*, 121133.

Addo-Quaye, A. A., Darkwa, A. A., & Ocloo, G. K. (2011). The yield and productivity of component crops in a maize-soybean intercropping system are affected by planting time and spatial arrangement. *Journal of Agricultural and Biological Science*, *6*(9), 50-57.

Adebayo, M. A., Bello, A. A., & Salau, T. A. (2022). Factors influencing the adoption of Bambara groundnut cultivation among smallholder farmers. *Journal of Agricultural Extension and Rural Development, 14*(1), 32-40.

Adegboyega, A., & Ogundele, O. (2021). Market potential and trade dynamics of Bambara groundnut: A review. Journal of Agricultural Economics, 72 (4), 1015-1029.

Adzawla, W., Donkoh S.A., George N., Reilly P., et al. (2016). Adoption of Bambara Groundnut Production and its effects on farmers' welfare in Northern Ghana. *African Journal of Agricultural Research, 11* (7), 583-594.

Afolabi, A. O., Ajibola, M. O., & Olaniyan, A. T. (2022). Effect of plant spacing on the growth and yield of bambara groundnut (Vigna subterranea). Journal of Crop Science and Biotechnology, 25 (1), 45-56.

Agu, H. O., Onuoha, G. O., Elijah, O. E., & Jideani, V. A. (2020). Consumer acceptability of acha and malted Bambara groundnut (BGN) biscuits sweetened with date palm. *Heliyon, 6*(11), e05522.

Ainsworth, E. A., & Long, S. P. (2021). Thirty years of free-air carbon dioxide enrichment (FACE): what have we learned about future crop productivity and its potential for adaptation? *Global Change Biology*, *27*(1), 27-49.

Akinnifesi, F. K., Makumba, W., Sileshi, G., Ajayi, O. C., & Mweta, D. (2007). Synergistic effect of inorganic N and P fertilisers and organic inputs from Gliricidia sepium on the productivity of intercropped maize in Southern Malawi. *Plant and Soil*, *294*, 203-217.

Akintoye, H. A., Ogunjimi, L. A., & Akinmoladun, A. I. (2022). Effect of intercropping Bambara groundnut with maize on growth, yield, and nutrient uptake. *Journal of Agricultural Science*, 14(3), 234-245. https://doi.org/10.1017/jas.2022.036

Akinyosoye, S., Agbeleye, O., Adetumbi, J., Bolarinwa, K., Oyeniyi, O., & Anjorin, F. (2023). Genetic Diversity of African Bambara Groundnut [Vigna subterranean (L) Verdc] Landraces for Yield Traits in Southwestern Agro-environments of Nigeria. *Journal of Underutilized Legumes, 5*(1), 1-14.

AL Hamdi, M. F. F., Ilyas, S., Qadir, A., & Mayes, S. (2024). Morphological variability and cluster analysis of 16 bambara groundnut (Vigna subterranea) genotypes. *Biodiversitas: Journal of Biological Diversity, 25*(1).

Alhassan, G. A., & Egbe, M. O. (2014). Bambara groundnut/maize intercropping: Effects of planting densities in Southern Guinea savanna of Nigeria. *African Journal of Agricultural Research*, *9*(4), 479-486.

Alhassan, G. A., B. A. Kalu, and O. M. Egbe. (2012). Influence of planting densities on the performance of intercropped Bambara groundnut with cowpea in Makurdi, Benue state, Nigeria.*International Journal of Development and Sustainability* 1.3: 860-879.

Ali, A. M., Darvishzadeh, R., Skidmore, A. K., & van Duren, I. (2017). Specific leaf area estimation from leaf and canopy reflectance through optimization and validation of vegetation indices. *Agricultural and forest meteorology*, *236*, 162-174.

Ali, M. M., Ahmed, A. F., & Hassan, M. S. (2023). Evaluating intercropping systems for improved productivity: A Bambara groundnut and sorghum case study. Agricultural Systems, 192, 103292.

Almeida, J. S., Souza, O. C., & Teixeira, L. S. (2018). Determination of Pb, Cu and Fe in ethanol fuel samples by high-resolution continuum source electrothermal atomic absorption spectrometry by exploring a combination of sequential and simultaneous strategies. *Microchemical Journal*, *137*, 22-26.

Al-Razgan, M., Alrowily, A., Al-Matham, R. N., Alghamdi, K. M., Shaabi, M., & Alssum, L. (2021). Using diffusion of innovation theory and sentiment analysis to analyze attitudes toward driving adoption by Saudi women. *Technology in Society*, *65* (23), 175-186.

Amsalu, A., & de Graaff, J. (2006). Farmers' views of soil erosion problems and their conservation knowledge at Beressa watershed, central highlands of Ethiopia. *Agriculture and Human Values*, *23*(1), 99–108.

Anas, M., Liao, F., Verma, K. K., Sarwar, M. A., Mahmood, A., Chen, Z. L., & Li, Y. R. (2020). Fate of nitrogen in agriculture and environment: agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. *Biological Research*, *53*(1), 1-20.

Ansa, J. E. O. (2016). Effects of groundnut spacing on yield and weed control in the rainforest agroecological zone of Nigeria. *Direct Research Journal of Agriculture and Food Science*, *4*(12), 374-377.

Aremu-Dele, O., Adesanya, K. A., Olorundare, B. O., Asunbo, O. I., & Odeyemi, E. F. (2021). Intercrop practices in cashew production. *World Journal of Advanced Research and Reviews*, *10*(3), 281-288

Asiwe, J. (2020). Effects of row spacing and weed infestation on yield of Bambara groundnut, Vigna subterranean (L.) Verdc. in South Africa. *Tropical Agriculture*, *97*(4).

Asiwe, J. A. N., & Maimela, K. A. (2020). Promotion Of Transformation Of Existing Cropping Practices Through The Introduction Of Modern Production Practices (Strip Intercropping Of Legumes With Maize) In Communities: Cowpea Variety Validation Trial And Strip Intercropping Of Cowpea With Maize Trial. *Legumes Ln Selected Rural Communltles Of Llmpopo Province, South Africa*, 8.

Audu, I., & Atiku, Z. A. (2021). Growth, Yield And Yield Components Of Ground Nut (Arachis Hypogea) As Affected By Spacing And Maize-Ground Nut Intercrop In Yola, Nigeria. *All Rights Reserved*, 51.

Aydın, Ü. N. A. Y., Sabanci, I., & Cinar, V. M. (2021). The Effect of Maize (Zea mays L.)/Soybean (Glycine max (L.) Merr.) Intercropping and Biofertilizer (Azotobacter) on Yield, Leaf Area Index and Land Equivalent Ratio. *Journal of Agricultural Sciences*, *27*(1), 76-82.

Ayenew, W., Lakew, T., & Kristos, E. H. (2020). Agricultural technology adoption and its impact on smallholder farmers welfare in Ethiopia. *African Journal of Agricultural Research*, *15*(3), 431-445.

Badu-Apraku, B., and Fakorede, M. A. B. (2017). “Maize in Sub-Saharan Africa: importance and production constraints,” in *Advances in Genetic Enhancement of Early and Extra-Early Maize for Sub-Saharan Africa,* eds B. Badu-Apraku, M. A. B. Fakorede (Cham: Springer International Publishing), 3–10. doi: 10.1007/978-3-319-64852-1_1

Barnes, A. P., Soto, I., Eory, V., Beck, B., et al. (2019). Exploring the adoption of precision agricultural technologies: A cross-regional study of EU farmers. *Land use policy*, *80*, pp163-174.

Barrett, C. A., Pas, E. T., & Johnson, S. L. (2020). A cost analysis of an evidence-based practice's innovation-decision process in schools. *School Mental Health*, *12*(3), 638-649.

Barton, L., & Li, X. (2022). Adapting Bambara groundnut (Vigna subterranea) for cultivation in Latin America: Insights from recent trials and research. *Agronomy, 12*(4), 792. https://doi.org/10.3390/agronomy12040792

Beillouin, D., Schauberger, B., Bastos, A., Ciais, P., & Makowski, D. (2020). Impact of extreme weather conditions on European crop production in 2018. *Philosophical Transactions of the Royal Society B, 375*(1810), 20190510.

Bendu, J. M., Mansaray, A., Bah, A. M., & Momoh, E. J. J. (2023) Effect of Planting Method and Spacing on the Yield and Yield Components of Three Bambara Groundnut Cultivars in two Agro-Climatic Zones of Sierra Leone.

Berchie, J. N. (2010). Variation in responses of Bambara groundnut (Vigna subterranea (l) verdc.) Landraces to sowing date, heat, photoperiod and drought *stresses* (Doctoral dissertation). Department of Crop and Soil Sciences, Faculty of Agriculture, Kwame Nkrumah University of Science and Technology (KNUST), pp. 222

Berchie, J. N., Opoku, M., Adu-Dapaah, H., Agyemang, A., & Sarkodie-Addo, J. (2012). Evaluation of five bambara groundnut (Vigna subterranea (L.) Verdc.) landraces to heat and drought stress at Tono-Navrongo, Upper East Region of Ghana. *African Journal of Agricultural Research*, *7*(2), 250-256.

Bernhard, B. J., & Below, F. E. (2020). Plant population and row spacing affect corn: Plant growth, phenology, and grain yield. *Agronomy Journal*, *112*(4), 2456-2465.

Bhutto, N., Rahman, A., Nahiyoon, A., Khan, A., & Zaman, B. (2018). Role of farmers' training on cotton production through farmer field school (FFS) approach in Sanghar, Sindh Pakistan. *International Journal of Farming and Allied. Science, 7*(1), 18-22.

Boateng, E. (2021). Response of plant spacing on the morphology and yield of five hot pepper lines. *African Journal of Agricultural Research*, *17*(10), 1281-1287.

Bonny, B. S., Adjoumani, K., Seka, D., Koffi, K. G., Kouonon, L. C., Koffi, K. K., & Bi, I. A. Z. (2019). Agromorphological divergence among four agroecological populations of Bambara groundnut (Vigna subterranea (L.) Verdc.) in Côte d'Ivoire. *Annals of Agricultural Sciences*, *64*(1), 103-111.

Boulay, B., Khan, R., & Morrissey, O. (2021). Under-utilised crops and rural livelihoods: Bambara groundnut in Tanzania. *Oxford Development Studies*, *49*(1), 88-103.

Castellini, G., Bruschettini, M., Gianola, S., Gluud, C., & Moja, L. (2018). Assessing imprecision in Cochrane systematic reviews: a comparison of GRADE and Trial Sequential Analysis. *Systematic Reviews*, *7*(1), 1-10.

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.

Chandio, A. A. & Yuansheng, J. I. A. N. G. (2018). Determinants of adoption of improved rice varieties in northern Sindh, Pakistan. *Rice Science, 25*(2), 103-110

Chapepa, B., Mudada, N., & Mapuranga, R. (2020). An overview of the impact of plant density and spatial arrangement on light interception on cotton crop and seed cotton yield. *Journal of Cotton Research*, *3*(1), 1-6.

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*(1), 9881028.

Chen, N., Li, X., Shi, H., Zhang, Y., Hu, Q., Ma, H., & Wang, B. (2023). Quantifying interspecies competition for water in tomato–corn intercropping system using an improved evapotranspiration model considering radiation interception by neighbouring plants in two-dimensional profile. *Scientia Horticulturae*, *310*, 111751.

Chimonyo, V. G. P., Govender, L., Nyathi, M., Scheelbeek, P. F. D., Choruma, D. J., Mustafa, M., & Mabhaudhi, T. (2023). Can cereal-legume intercrop systems contribute to household nutrition in semi-arid environments: A systematic review and meta-analysis—frontiers *in nutrition*, *10*, 84.

Chimonyo, V. G., Wimalasiri, E. M., Kunz, R., Modi, A. T., & Mabhaudhi, T. (2020). Optimizing traditional cropping systems under climate change: a case of maize landraces and Bambara groundnut. *Frontiers in Sustainable Food Systems*, *4*, 562568.

Chinedu, S. N., & Nwinyi, C. O. (2012). Proximate analysis of *Sphenostylis stenocarpa* and *Voadzeia subterranean* consumed in South-Eastern Nigeria. *Journal of Agricultural Extension and Rural Development*, *4*(3), 57–62.

Chivenge, P., Mabhaudhi, T., Modi, A. T., & Mafongoya, P. (2015). The potential role of neglected and underutilised crop species as future crops under water-scarce conditions in Sub-Saharan Africa. *International Journal of Environmental Research and Public Health*, *12*(6), 5685–5711.

Cochran, W. G. (2007). *Sampling techniques*. John Wiley & Sons.

Creissen, H. E., Jones, P. J., Tranter, R. B., Girling, R. D., Jess, S., Burnett, F. J., & Kildea, S. (2021). Identifying the drivers and constraints to the adoption of IPM among arable farmers in the UK and Ireland. *Pest Management Science*, *77*(9), 4148-4158.

Dakora, F. D., Aboyinga, R. A., Mahama, Y., and Apaseku, J. (1987). Assessment of N_2 fixation in groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* L. Walp) and their relative N contribution to a succeeding maize crop in Northern Ghana. *MIRCEN J. Appl. Microbiol. Biotechnol.* 3, 389–399. doi: 10.1007/BF00935697

Dang, K., Gong, X., Zhao, G., Wang, H., Ivanistau, A., & Feng, B. (2020). Intercropping alters the soil microbial diversity and community to facilitate nitrogen assimilation: a potential mechanism for increasing proso millet grain yield. *Frontiers in Microbiology*, *11*, 601054.

Dariush, M., Ahad, M., & Meysam, O. (2006). Assessing the land equivalent ratio (LER) of two corn [Zea mays L.] varieties intercropping at various nitrogen levels in Karaj, Iran. *Journal of Central European Agriculture*, *7*(2), 359-364.

Dauna, J.U. (2013). Economic Meltdown and Decline in Groundnut Production: Determinant of Production Inefficiency of Groundnut-Based Alley Cropping Practices in Cross River State, Nigeria. J. Anim. Plant Sci. 20(2):107-116.

Diedericks, C. F., & Jideani, V. A. (2015). Physicochemical and functional properties of insoluble dietary fibre isolated from Bambara groundnut (Vigna subterranean [L.] Verdc.). *Journal of Food Science*, *80*(9), 1933-1944.

Dikr, W., & Tadesse, N. (2022). Screening Common Bean Varieties Compatibility to Intercropping with Maize at Jejebicho Research Station in Sankura Wereda Silte Zone of Southern Ethiopia. *American Journal of Plant Biology*, *7*(1), 15-25.

Dlamini, S. T., Jaiswal, S. K., Mohammed, M., & Dakora, F. D. (2021). Studies of phylogeny, symbiotic functioning and ecological traits of indigenous microsymbionts nodulating bambara groundnut (Vigna subterranea L. Verdc) in Eswatini. *Microbial ecology*, 1-16.

Dodd, J., Sweby, P. K., Mayes, S., Murchie, E. H., Karunaratne, A. S., Massawe, F., & Tindall, M. J. (2023). A multiscale mathematical model describing the growth and development of bambara groundnut. *Journal of Theoretical Biology*, *560*, 111373.

Dube, E., Moyo, N., & Ndlovu, N. (2021). Nutritional benefits and household utilisation of Bambara groundnut. Food Security, 13 (6), 1575-1587.

Dubey, R., Pathak, H., Chakrabarti, B., Singh, S., Gupta, D. K., & Harit, R. C. (2020). Impact of terminal heat stress on wheat yield in India and options for adaptation. *Agricultural Systems*, *181*, 102826.

Effa, E., Nwagu, F., Osai, E., & Shiyan, J. (2016). Growth and yield response of Bambara groundnut (*Vigna subterranea* (L.) Verdc.) to varying densities and Phosphate fertilizer rates in Calabar, South Eastern Nigeria. *Journal of Biology, Agriculture and Healthcare*, *6*(16), 14–20.

Egbe, M. O. (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.

Egbe, M. O. (2016). 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.

Eifediyi, E. K., Ahamefule, H. E., Izuogu, B. N., Ogedegbe, F. O., & Remison, S. U. (2020). Growth and yield of bambara groundnut (Vigna subterranea L. Verdc) as influenced by tillage and phosphorus application.

Feldman, A. B., Mayes, S., Kendabie, P., Kuan, H. W., Halimi, R. A., Massawe, F., & Azam-Ali, S. (2019a). Challenges facing genetically improving underutilized crops: Progress in bambara groundnut. *Acta Horticulturae, 1241*, 215–220.

Feldman, A., Ho, W. K., Massawe, F., & Mayes, S. (2019b). Bambara Groundnut is a Climate-Resilient Crop: How Could a Drought-Tolerant and Nutritious Legume Improve Community Resilience in the Face of Climate Change? In *Sustainable Solutions for Food Security* (pp. 151–167).

Feng, C., Sun, Z., Zhang, L., Feng, L., Zheng, J., Bai, W., & van der Werf, W. (2021). Maize/peanut intercropping increases land productivity: A meta-analysis. *Field Crops Research*, *270*, 108208.

Fujita, K., & Ofosu-Budu, K. G. (1996). Significance of intercropping in cropping systems. *Dynamics of Roots and Nitrogen in Cropping Systems of the Semi-Arid Tropics. Japan International Research Center for Agricultural Sciences. International Agricultural Series*, (3), 19-40.

Gachimbi, L. N., Kamoni, P. T., Wanjogu, S. N., Macharia, P. N., & Gicheru, P. T. (2007). Land Use Practices in Mbeere District: Biophysical and Socio Economic Challenges, Copping Strategies and Opportunities: A Baseline Survey Report. *Kenya Agricultural Livestock and Research Organization. Nairobi. Kenya*.

Garkebo, H., & Abera, G. (2020). Effects of Interseeded Green Manure Legume Species and Termination Time on the Performance of Maize (Zea Mays L) Crop and Soil Characteristics.

Garland, G., Edlinger, A., Banerjee, S., Degrune, F., García-Palacios, P., Pescador, D. S., & van der Heijden, M. G. (2021). Crop cover is more important than rotational diversity for soil multifunctionality and cereal yields in European cropping systems. *Nature Food*, *2*(1), 28-37.

Gbenyi, D. I., Nkama, I., & Badau, M. H. (2016). Optimization of Physical and Functional Properties of Sorghum-Bambara Groundnut Extrudates. *Journal of Food Research*, *5*(2), 81.

Gerrano, A. S., Eifediyi, E. K., Labuschagne, M., Ogedegbe, F. O., & Hassen, A. I. (2021). Production Practices of Bambara Groundnut. In *Food and Potential Industrial Applications of Bambara Groundnut . Springer*, (pp. 7-25).

Gezahegn, A. M. (2019). Review on effect of plant density and planting arrangement on faba bean production. *World Journal of Agricultural Sciences*, *15*(4), 261-268.

Gitari, J. N., Matiri, F. M., Kariuki, I. W., Muriithi, C. W., & Gachanja, S. P. (1999). *Nutrient and cash flow monitoring in farming systems on the Eastern slopes of Mount Kenya*. CABI Publishing.

Gonzalez, J. C., Mercado, J. F., & Campos, R. M. (2021). Advances in agronomic practices for Bambara groundnut: A review. *Field Crops Research*, 268, 1081-1094. https://doi.org/10.1016/j.fcr.2021.1081

Government of Kenya (GoK) (2007). Vision 2030 First medium term plan (2008 - 2012). *Government Printers*, 1–218.

Gupta, A., Rico-Medina, A., & Caño-Delgado, A. I. (2020). The physiology of plant responses to drought. *Science*, *368*(6488), 266-269.

Hantgan, A. (2024). Layers of Lexical Borrowing in Long-Term Contact Rooted among Ancient Crops from Mali's Bandiagara Region. *Journal of Language Contact*, *16*(4), 494-564.

Haque, M. A., & Sakimin, S. Z. (2022). Planting Arrangement and Effects of Planting Density on Tropical Fruit Crops—A Review. *Horticulturae, 8*(6), 485.

Harisha, C. B., Rane, J., Halagunde Gowda, G. R., Chavan, S. B., Chaudhary, A., Verma, A. K., ... & Reddy, K. S. (2024). Effect of Deficit Irrigation and Intercrop Competition on Productivity, Water Use Efficiency and Oil Quality of Chia in Semi-Arid Regions. *Horticulturae*, *10*(1), 101.

Hasan, M., Uddin, K., Mohamed, M. T. M., & Zuan, A. T. (2018). Nitrogen and phosphorus management for Bambara groundnut (Vigna subterranea) production-A review. *Legume Research-An International Journal*, *41*(4), 483-489.

Hasan, M., Uddin, M. K., Mohammed, M., Zuan, A. K., & Motmainna, M. (2019). Impact of nitrogen and phosphorus fertilizer on growth and yield of Bambara groundnut. *Plant Archives*, *19*(1), 501-504.

Heuzé, V., Tran, G., Bastianelli, D., Archimede, H., & Sauvant, D. (2013). Feedipedia: an open access international encyclopedia on feed resources for farm animals. Wageningen Academic Publishers.

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).

Hlanga, N., (2021). *Agro-morphological, nutritional and genetic diversity analyses of bambara groundnut (Vigna subterranea (L.) Verdc)* (Doctoral dissertation).

Holt, R., Watson, C. A., & Topp, C. F. E. (2021). Identifying the research gaps in cereal-grain legume intercropping. In *Legume Science and Practice 2*.

Hou, P., Liu, Y., Liu, W., Liu, G., Xie, R., Wang, K., & Li, S. (2020). How to increase maize production without extra nitrogen input. *Resources, Conservation and Recycling*, *160*, 104913.

Hunter, M. C., Sheaffer, C. C., Culman, S. W., & Jungers, J. M. (2020). Effects of defoliation and row spacing on intermediate wheatgrass I: Grain production. *Agronomy Journal*, *112*(3), 1748-1763.

Hussain, S., Huang, J., Huang, J., Ahmad, S., Nanda, S., Anwar, S., & Zhang, J. (2020). Rice production under climate change: adaptations and mitigating strategies. *Environment, climate, plant and vegetation growth*, 659-686.

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.

Ibrahim, A. M., Bala, U. M., & Halima, M. I. (2024). Impact of seedbed types and scarification methods on germination percentage and growth performance of Bambara groundnut (Vigna subterranea (L.) Verdc.) in the Sudan Savanna zone of Nigeria. *Journal of Current Opinion in Crop Science*, *5*(2), 93-102.

Ike, K. A., Nwaigbo, L. C., Obasi, C. P., Olanite, J. A., & Chilaka, O. M. (2013) Effect of Fertilizer LEVEL and Intercropping with Bambara Nut (Vigna subterranea) on the Growth and Herbage Yield of Maize.

International Plant Genetic Resources Institute. (1997). *Descriptors for pistachio (Pistacia vera L.)*. International Plant Genetic Resources Institute. http://www.cgiar.org/ipgri/

Jackson, S. L., Spence, J., Janssen, D. J., Ross, A. R. S., & Cullen, J. T. (2018). Determination of Mn, Fe, Ni, Cu, Zn, Cd and Pb in seawater using offline extraction and triple quadrupole ICP-MS/MS. *Journal of analytical atomic spectrometry*, *33*(2), 304-313.

Jensen, E. S., Ambus, P., Bellostas, N., Boisen, S., Brisson, N., Corre-Hellou, G. & Gooding, M. (2007). Intercropping of cereals and grain legumes for increased production, weed control, improved product quality and prevention of N-losses in

European organic farming systems. In *Danish Research Centre for Organic Food and Farming, DARCOF Proceedings* (pp. 180-181).

Jensen, E. S., Carlsson, G., & Hauggaard-Nielsen, H. (2020). Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-scale analysis. *Agronomy for Sustainable Development*, *40*(1), 1-9.

Jensen, E.S., Bedoussac, J., Carlsson, G., Journet, E.P., Justes, E., & Hauggaard N. (2015). Enhancing yields in organic crop production by eco-functional intensification. *Sustain. Agric. Res*. 4:42–50.

Jia, Q., & Wang, Y. P. (2021). Relationships between leaf area index and evapotranspiration and crop coefficient of hilly apple orchard in the Loess Plateau. *Water*, *13*(14), 1957.

Kader, M. A., Jahangir, M. M. R., Islam, M. R., Begum, R., Nasreen, S. S., Islam, M. R., & Jahiruddin, M. (2022). Long-term conservation agriculture increases nitrogen use efficiency by crops, land equivalent ratio and soil carbon stock in a subtropical rice-based cropping system. *Field Crops Research*, *287*, 108636.

Kaluba, P., Mwamba, S., Moualeu-Ngangue, D. P., Chiona, M., Munyinda, K., Winter, E., & Chishala, B. H. (2022). Performance of Cassava under Lime, Fertilizer, and Legume Intercropping on Exhausted Land in Northern Zambia. *International Journal of Agronomy*.

Kaminski, J. (2012). Theory in Nursing Informatics Column. *Canadian Journal of Nursing Informatics*, *6*(2), 1–7.

Karunaratne, A. S., Azam-Ali, S. N., Al-Shareef, I., Sesay, A., Jørgensen, S. T., & Crout, N. M. J. (2010). Modelling the canopy development of bambara groundnut. *Agricultural and Forest Meteorology*, *150*(7-8), 1007-1015.

Karunaratne, A. S., Azam-Ali, S. N., Izzi, G., & Steduto, P. (2011). Calibration and validation of FAO-AquaCrop model for irrigated and water deficient bambara groundnut. *Experimental Agriculture*, *47*(3), 509-527.

Karunaratne, A. S., Walker, S., & Ruane, A. C. (2015). Modelling Bambara groundnut yield in Southern Africa: Towards a climate-resilient future. *Climate Research*, *65*, 193-203.

Kebede, E. (2020). Grain legumes production and productivity in Ethiopian smallholder agricultural system, contribution to livelihoods and the way forward. *Cogent Food & Agriculture*, *6*(1), 1722353.

Keerthi, M. M., Babu, R., Joseph, M., & Amutha, R. (2015). Optimizing plant geometry and nutrient management for grain yield and economics in irrigated greengram. *American Journal of Plant Sciences*, *6*(08), 1144.

Kenya National Bureau of Statistics (KNBS) (2019). *2019 Kenya Population and Housing Census Volume I : Population By County and Sub-County*. Retrieved from http://www.knbs.or.ke on 11/07/2022.

Khan, M. M. H., Rafii, M. Y., Ramlee, S. I., Jusoh, M., & Mamun, M. (2021). 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.

Kimani, P., Mwangi, J., & Muthoni, R. (2023). Promoting Bambara groundnut cultivation in drylands: Challenges and opportunities in Embu County, Kenya. *International Journal of Agricultural Sustainability, 21*(3), 207-223.

Kiwia, A.; Kimani, D.; Harawa, R.; Jama, B.; Sileshi, G.W. (2019) Sustainable Intensification with Cereal-Legume Intercropping in Eastern and Southern Africa. *Sustainability , 11*, 2891

Konan, K. M., Kouassi, K. I., Bonny, B. S., Doubi, B. T. S., Zoro, B. I. A., & Dogbo, D. O. (2023). The efficiency of cassava–Bambara groundnut intercropping according to the sowing date of cassava. *South African Journal of Plant and Soil*, 1-9.

Kouassi, N., & BI, I. Z. (2010). Effect of sowing density and seedbed type on yield and yield components in bambara groundnut (Vigna subterranea) in woodland savannas of Cote d'Ivoire. *Experimental Agriculture*, *46*(1).

Kumar, D., Kiran, S. K., & Kumar, B. (2022). Bambara Groundnut: A Highly Neglected Complete Food Leguminous Crop in India.

Lailogo, O. T., Suva, M. M., Torres, C. S., Jamias, S. B., & Baconguis, R. B. (2018). Participatory communication among farmers in rice integrated crop management-farmer field School (Ricm-Ffs), East Nusa Tenggara Province, Indonesia, *International Journal of Agriculture Innovations and Research*. 6(4).

Le Blanc, D. (2015). Towards Integration at Last? The Sustainable Development Goals as a Network of Targets. *Sustainable Development*, *23*(3), 176–187. .

Legodi, K. D., & Ogola, J. B. O. (2020). Cassava-legume intercrop: I. Effects of relative planting dates of legumes on cassava productivity. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, *70*(2), 150-157.

Lengwati, D. M., Mathews, C., & Dakora, F. D. (2020). Rotation benefits from N2-fixing grain legumes to cereals: From increases in seed yield and quality to greater household cash income by a following maize crop. *Frontiers in Sustainable Food Systems*, *4*, 94.

Li, H., Huang, J., Song, Y., Zhang, M., Wang, H., Lu, F. & Kang, Z. (2018). Degradable carbon dots with broad-spectrum antibacterial activity. *ACS applied materials & interfaces*, *10*(32), 26936-26946.

Liliane, T. N., & Charles, M. S. (2020). Factors affecting yield of crops. *Agronomy-climate change & food security*, 9.

Mabhaudhi, T., Modi, T., & Beletse, G. (2013). Growth, phenological and yield responses of a Bambara groundnut (Vigna subterranean L. Verdc) landrace to imposed water stress: II. Rain shelter conditions. *Water Sa*, *39*(2), 191-198.

MacLaren, C., Waswa, W., Aliyu, K. T., Claessens, L., Mead, A., Schöb, C., & Storkey, J. (2023). Predicting intercrop competition, facilitation, and productivity from simple, functional traits. *Field Crops Research, 297*, 108926.

Maitra, S., Palai, J. B., Manasa, P., & Kumar, D. P. (2019). The potential of the intercropping system in sustaining crop productivity. *International Journal of Agriculture, Environment and Biotechnology*, *12*(1), 39-45.

Majola, 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.

Makanda, I., Tongoona, P., Madamba, R., Icishahayo, D., & Derera, J. (2008). Evaluation of Bambara groundnut varieties for off-season production in Zimbabwe. *African Crop Science Journal*, *16*(3).

Makate, C., Makate, M., Mango, N., & Siziba, S. (2019). Increasing resilience of smallholder farmers to climate change through multiple adoptions of proven climate-smart agriculture innovations. Lessons from Southern Africa. *Journal of Environmental Management*, *231*, 858-868.

Mango, N., Makate, C., Tamene, L., Mponela, P., & Ndengu, G., (2017). Awareness and adoption of land, soil and water conservation practices in the Chinyanja Triangle, Southern Africa. *International Soil and Water Conservation Research*, *5*(2), pp122-129.

Maphosa, Y., Jideani, V. A., & Maphosa, L. (2022). Bambara groundnut production, grain composition and nutritional value: opportunities for improvements. *The Journal of Agricultural Science*, *160*(6), 448-458.

Marie, M., Yirga, F., Haile, M., & Tquabo, F. (2020). Farmers' choices and factors affecting climate change adaptation strategies adoption: evidence from northwestern Ethiopia. *Heliyon*, *6*(4), e03867.

Marshall, T., Ibarra, M., & Patel, R. (2024). *Root system characteristics and their implications for intercropping: A study of sorghum and Bambara groundnut*. *Field Crops Research, 340,* 108662. https://doi.org/10.1016/j.fcr.2024.108662

Masindeni M. (2006). Evaluation of Bambara groundnut (Vignasubterranea) for yield stability and yield-related characteristics. M.Sc. Thesis, University of the Free State, Bloemfontein, South Africa.

Massawe, F.J., Azam-Ali, S.N., Roberts, J.A., 2003. The impact of temperature on leaf appearance in Bambara groundnut landraces. Crop Sci. 43, 1375-1379.

Masvaya, E. N., Nyamangara, J., Descheemaeker, K., & Giller, K. E. (2017). Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid southern Africa? *Field Crops Research, 209,* 73-87.

Mateva, I., Tan, L., Halimi, A., Chai, H., Makonya, G. M., Gao, X., & Massawe, F. (2023). Bambara groundnut (Vigna subterranea (L.) Verdc.). In *Neglected and Underutilized Crops* (pp. 557-615). Academic Press.

Matthews, N., and McCartney, M. (2018). Opportunities for building resilience and lessons for navigating risks: dams and the water energy food nexus. *Environ. Prog. Sustain. Energy* 37, 56–61. doi: 10.1002/ep.12568

Mattila, T. J., & Rajala, J. (2022). Do different agronomic soil tests identify similar nutrient deficiencies? *Soil Use and Management*, *38*(1), 635-648.

Mawiya, W. (2016). *Effect of genotype and plant population on growth, nitrogen fixation and yield of soybean [Glycine max (L.) Merrill] in the Sudan Savanna Agro-Ecological Zone of Ghana* (Doctoral dissertation)

Mayes, S., Chai, H., Gao, X., Kundy, C., Mateva, I., & Azam, N. (2019). Bambara groundnut: an exemplar underutilised legume for resilience under climate change. *Planta*. Volume 250, Issue 3, pp 803–820

Mazahib, M., Nuha, O., SalawaS., & Babiker E., (2013). Some nutritional attributes of Bambara groundnut as influenced by domestic processing. *International Food Research Journal*, *20*(3), 1165–1171.

Mazur, V. A., Pantsyreva, H. V., Mazur, K. V., & Didur, I. M. (2019). Influence of the assimilation apparatus and productivity of white lupine plants.

Mazzafera, P., Favarin, J. L., & Andrade, S. A. L. D. (2021). Intercropping systems in sustainable agriculture. *Frontiers in Sustainable Food Systems*, *5*, 634361.

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

Mensah, G. (2011). *Modification of Bambara Groundnuts Starch, Composited with Defatted Bambara Groundnut Flour for Noodle Formulation* (Doctoral dissertation). Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

Mishra, A., Kumar, S., & Singh, R. (2023). *Effectiveness of legume-cereal intercropping in improving soil health and productivity in smallholder farming systems*. *Field Crops Research*, *295*, 108575. https://doi.org/10.1016/j.fcr.2023.108575

Mkandawire, C. H. (2007). Review of bambara groundnut (*Vigna subterranea* (L.) Verdc.) production in Sub-Sahara Africa. *Agricultural Journal*, *2*(4), 464-470.

Mogaka, B. O., Bett, H. K., & Karanja Ng'ang'a, S. (2021). Socioeconomic factors influencing the choice of climate-smart soil practices among farmers in western Kenya. *Journal of Agriculture and Food Research*, *5*, 100168.

Mohammed, I. Y., Abakr, Y. A., Musa, M., Yusup, S., Singh, A., & Kazi, F. K. (2016). Valorization of Bambara groundnut shell via intermediate pyrolysis: Products distribution and characterization. *Journal of Cleaner Production*, *139*, 717–728.

Mohammed, S. E. I. D. U. (2019). *Impact Of Spatial Arrangement On Growth, Yield And Profitability Of Maize–Groundnut Intercropping System* (Doctoral dissertation).

Mohammed, S. M. (2014). *Pre-breeding of Bambara groundnut (Vigna subterranea [L.] Verdc.)* (Doctoral dissertation).

Molatudi, R. L., & Mariga, I. K. (2012). Grain yield and biomass response of a maize/dry bean intercrop to maize density and dry bean variety. *African Journal of Agricultural Research*, *7*(20), 3139-3146.

Molefe, M., Moyo, N., & Shongwe, N. (2020). The economic impact of Bambara groundnut cultivation in smallholder farming systems. African Journal of Agricultural Research, 15 (9), 1121-1130.

Moreira, B., Gonçalves, A., Pinto, L., Prieto, M. A., Carocho, M., Caleja, C., & Barros, L. (2024). Intercropping Systems: An Opportunity for Environment Conservation within Nut Production. *Agriculture*, *14*(7), 1149.

Moser, C. M., & Barrett, C. B. (2003). The disappointing adoption dynamics of a yield-increasing, low external-input technology: The case of SRI in Madagascar. *Agricultural Systems*, *76*(3), 1085–1100.

Moyo, N., Chikwendu, A. I., & Moyo, S. (2021). Bambara groundnut: A climate-resilient legume for sustainable agriculture. *Agricultural Systems, 191*, 103144.

Mugendi, D., Mucheru-Muna, M., Mugwe, J., Kung'u, J., & Bationo, A. (2007). Improving food production using 'best bet' soil fertility technologies in the Central highlands of Kenya. *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities*, (1996), 345–351.

Mugi-Ngenga, E., Bastiaans, L., Anten, N. P. R., Zingore, S., Baijukya, F., & Giller, K. E. (2023). The role of inter-specific competition for water in maize-legume intercropping systems in northern Tanzania. *Agricultural Systems*, *207*, 103619.

Mugwe, J., Mugendi, D. N., Mucheru-Muna, M., & Kung'u, J. B. (2011). Soil inorganic N and N uptake by maize following application of legume biomass, tithonia, manure and mineral fertilizer in Central Kenya. In *Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts* (pp. 605-616). Springer Netherlands.

Mugwe, J., Mugendi, D., Mucheru-Muna, M., Merckx, R., Chianu, J., & Vanlauwe, B. (2009). Determinants of the decision to adopt integrated soil fertility management practices by smallholder farmers in the central highlands of Kenya. *Experimental Agriculture*, *45*(1), 61–75.

Muhammad, I., Rafii, M. Y., Ramlee, S. I., Nazli, M. H., Harun, A. R., Oladosu, Y., & Arolu, I. W. (2020). Exploration of bambara groundnut (Vigna subterranea (L.) Verdc.), an underutilized crop, to aid global food security: Varietal improvement, genetic diversity and processing. *Agronomy*, *10*(6), 766.

Mukhtar, A.A. 2009. Performance of three groundnut (Arachis hypogaea L.) varieties as affected by basin size and plant population at Kadawa. Ph.D. Dissertation Submitted to Post Graduate School, Ahmadu Bello University, Zaria, pp. 173

Muleba, N., Ouedraogo, J. T., Drabo, I., & Dabire, C. (1997). Improving the efficiency in breeding cowpeas for production in semi-arid tropics. *African Crop Science Journal*, *5*(4).

Musah, M., Azeh, Y., Mathew, J. T., Nwakife, N. C., Mohammed, A. I., & Saidu, F. (2021). Nutritional evaluation of bambara groundnut (Vigna subterranea (L.) Verdc) from Lapai, Nigeria.

Musyoka, J. K., Isaboke, H. N., & Ndirangu, S. N. (2020). Farm-level value addition among small-scale mango farmers in Machakos County, Kenya. *Journal of Agricultural Extension*, *24*(3), 85-97.

Mwale, S. S., Azam-Ali, S. N., & Massawe, F. J. (2007). Growth and development of Bambara groundnut (Vigna subterranean) in response to soil moisture. *European Journal of Agronomy*, *26*(4), 345–353.

Mwangi, J. W., Karanja, D. D., & Mutiso, M. N. (2023). Influence of plant spacing on the agronomic performance of Bambara groundnut in semi-arid regions. Field Crops Research, 284, 108423.

Naazie, G. K., Dakyaga, F., & Derbile, E. K. (2023). Agro-ecological intensification for climate change adaptation: Tales on soil and water management practices of smallholder farmers in rural Ghana.

Naeem, A., Ahmad, Z., Akhtar, A. and Muhammad, J. (2015). Effect of Earthing up Procedure on 25 Enhancement in Yield of Different Groundnut Varieties Planted under Agro - Climatic Conditions of Malakand Division. Journal of Agriculture and Environmental Sciences. 4(1): 181-184.

Namdari, M., Abbasi, R., Pirdashti, H., & Zaefarian, F. (2021). Effect of competition on morphological, physiological and productivity characteristics in soybean (Glycine max (L) Merrill) and millet (Panicum miliaceum L.) intercropping. *Journal Of Agroecology*.

Nassary, E. K., Baijukya, F. P., & Ndakidemi, P. A. (2019). Sustainable intensification of grain legumes optimizes food security on smallholder farms: a review. *International Journal of Agriculture and Biology*.

Naudin, C., Corre-Hellou, G., Pineau, S., Crozat, Y., & Jeuffroy, M. H. (2010). The effect of various dynamics of N availability on winter pea-wheat intercrops: Crop growth, N partitioning and symbiotic N 2 fixation. *Field Crops Research*, *119*(1), 2–11.

Nderi, L. M. (2020). *Effect of different spacing intervals on growth and yield of cowpea varieties in Kilifi County, Kenya* (Doctoral dissertation, KeMU).

Ndjadi, S. S., Vissoh, P. V., Vumilia, R. K., Mondo, J. M., Mugumaarhahama, Y., Saidou, A., ... & Ahoton, L. E. (2022). Yield potential and land-use efficiency of onion (Allium cepa L.) intercropped with peanut (Arachis hypogaea L.) under organic soil fertility management in South-Kivu, Eastern DR Congo. *Bulgarian Journal of Agricultural Science*, *28*(4).

Ng, Y. M. (2020). Re-examining the innovation post-adoption process: The case of Twitter discontinuance. *Computers in Human Behavior*, *103*, 48-56.

Ngairangbam, H., Kaur, A. P., Singh, G., & Menon, S. (2024). Effect of Different Spacing and Nutrient Management on Growth and Yield of Maize: A Review. *Journal of Advances in Biology & Biotechnology, 27*(6), 682-692.

Ngetich, F. K., Shisanya, C. A., Mugwe, J., Mucheru-Muna, M., & Mugendi, D. (2012). The Potential of Organic and Inorganic Nutrient Sources in Sub-Saharan African Crop Farming Systems. In (Ed.), *Soil Fertility Improvement and Integrated Nutrient Management - A Global Perspective*. IntechOpen. https://doi.org/10.5772/28728

Ngetich, K. F., Mucheru-Muna, M., Mugwe, J. N., Shisanya, C. A., Diels, J., & Mugendi, D. N. (2014). Length of growing season, rainfall temporal distribution, onset and cessation dates in the Kenyan highlands. *Agricultural and Forest Meteorology*, *188*, 24-32.

Nguyen, T. D., Zhang, L., & Ahmed, M. (2024). *Impact of intercropping Bambara groundnuts with sorghum on soil nutrient dynamics and crop yields*. *Agricultural Systems, 213*, 103831. https://doi.org/10.1016/j.agsy.2024.103831

Nhamo, L., Mathcaya, G., Mabhaudhi, T., Nhlengethwa, S., Nhemachena, C., Mpandeli, S. (2019). Cereal production trends under climate change: impacts and adaptation strategies in Southern Africa. *Agriculture* 9:30. doi: 10.3390/agriculture9020030

Njeri, J. M., Mwangi, J. N., & Mutiso, M. K. (2023). The potential of Bambara groundnut as a sustainable crop in emerging markets: Insights from recent studies. *Agricultural Systems*, 205, 103456. https://doi.org/10.1016/j.agsy.2022.103456

Njeru, P. N., Maina, M., Mugwe, J., Mugendi, D., & Lekasi, J. K. (2013). Integrating farmer's evaluation with scientific methods for assessing climate change mitigation options towards sorghum productivity in Mbeere sub-County. *Joint proceedings of the 27th Soil Science Society of East Africa and the 6th African Soil Science Society*

Njira, K. O., Semu, E., Mrema, J. P., & Nalivata, P. C. (2021). Productivity of pigeon pea, cowpea and maize under sole cropping, legume–legume and legume–cereal intercrops on Alfisols in Central Malawi. *Agroforestry Systems*, *95*, 279-291.

Ntshangase, N. L., Muroyiwa, B., & Sibanda, M., (2018). Farmers' perceptions and factors influencing the adoption of no-till conservation agriculture by small-scale farmers in Zashuke, KwaZulu-Natal Province. *Sustainability, 10*(2), 555-569.

Nweke, I. A. (2020). Potentials of Intercropping Systems to Soil-Water-Plant-Atmosphere. *Agricultural Science*, *2*(1), 31-31.

Nweke, I. A., & Anene, O. H. (2019). Effect of maize/bambara groundnut inter-crop on soil properties, growth and yield parameter of the intercrop species. *Eur. J. Agriculture Forestry Res*, *7*, 16-28.

Nwosu, J. N. (2013). Production and evaluation of biscuits from blends of Bambara Groundnut (*Vigna Subterranae*) and Wheat (*Triticum Eastrum*) flours. *International journal of food and nutrition science*, *2*(1), 4-9.

Nyasimi, M., Kimeli, P., Sayula, G., Radeny, M., Kinyangi, J., & Mungai, C. (2017). Adoption and dissemination pathways for climate-smart agriculture technologies and practices for climate-resilient livelihoods in Lushoto, Northeast Tanzania. *Climate*, *5*(3), 63-70.

Obura, M. (2021). Effect of phosphorus fertilizer rates and priming treatments on seed quality of Bambara Groundnut (*Vigna subterranea* (L.) Verdc.) (Unpublished PhD thesis submitted to the University of Eldoret).Kenya.

Ogbuagu, S., Okoye, N. N., & Innocent, C. L. (2023). Vigna subterranean (Bambara groundnut), a possible weapon in fighting the malnutrition war in the arid and sub-arid regions. *World Journal of Advanced Research and Reviews*, *17*(3), 242-249.

Ogwu, M. C., Ahana, C. M., & Osawaru, M. E., (2018). Sustainable food production in Nigeria: a case study for Bambara Groundnut (*Vigna subterranea* (L.) Verdc. Fabaceae). *Journal of Energy and Natural Resource Management, 4*(2), 187-196

Okeoghene, S. (2020). Management of cocoa black pod disease by farmers in Edo State, Nigeria: The role of farmer field school. *Development*, *10*(2), 528-540.

Oladimeji, B. M., & Adebo, A. (2024). Properties and metabolite profiling of Bambara groundnut flour as affected by different food processing conditions. *Applied Food Research*, *4*(1), 100389.

Olanrewaju, O. S. (2022). *Analysis of Bambara groundnut (Vigna subterranea (L.) Verdc.) diversity towards improved yield* (Doctoral dissertation, North-West University (South Africa).

Olanrewaju, O. S., Oyatomi, O., Babalola, O. O., & Abberton, M. (2021). GGE Biplot analysis of genotype× environment interaction and yield stability in bambara groundnut. *Agronomy*, *11*(9), 1839.

Olanrewaju, S., Oyatomi, O., Babalola, O. O., & Abberton, M. (2022). Breeding potentials of Bambara groundnut for food and nutrition security in the face of climate change. *Frontiers in Plant Science*, *12*, 798993.

O'Neill, J., & Hartmann, P. (2023). *Intercropping legumes and cereals: Enhancing soil fertility and resilience in smallholder farming systems*. *Agricultural Systems, 208,* 103722. https://doi.org/10.1016/j.agsy.2023.103722

Onuche, U., Ibitoye, S. J., & Anthony, T. (2020). Profitability and efficiency of Bambara groundnut production in Nigeria: A case study. *Review of Agricultural and Applied Economics (RAAE), 23*(2), 92-101.

Onuk E.G., Salau E.S., and Saleh, A. (2017). Economic of Maize-Cowpea Intercropped Production in Kokona Local Government Area of Nasarawa State, Nigeria. World Academic Research Journal of Agriculture and Global Food Security Vol. 2 (3), pp 200 – 205, July, 2017

Onyango, K. R. (2017). Emerging Lessons from Medium Sized Public Private Partnerships (PPPs) in the Kenyan Water Sector. *Journal of Economics and Sustainable Development*, *8*(22), 70–75.

Ortiz-Bobea, A., Ault, T. R., Carrillo, C. M., Chambers, R. G., & Lobell, D. B. (2021). Anthropogenic climate change has slowed global agricultural productivity growth. *Nature Climate Change, 11*(4), 306-312.

Osei, A., Afriyie, E., & Addai, E. K. (2022). Synergistic effects of intercropping bambara groundnut with sorghum: A review. Journal of Agricultural and Food Research, 9, 100386.

Ouedraogo, M., Zagre, B., Thorndal, S. and Liu, F. (2012). Effect of earthing up times on yield of Bambara groundnut landraces in Sahel-Burkina Faso. African Journal of Agriculture Research. 7: 4505-4511.

Oyewole, O. O., Oladele, S., Awodun, M., & Ajala, R. (2018). Evaluation of four microbial bio-effectors for growth promotion and nutrient acquisition in Bambara nut *Vigna subterranea* (L.) Verdc. (Fabales: Fabaceae) without mineral fertilization. *Brazilian Journal of Biological Sciences*, *5*(11), 837–849.

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.

Oyugi, M., Nandi, O., Amudavi, D., & Palapala, V. (2015). Influence of Gender on Farmers' level of Involvement in Bambara Production Activities in Western Kenya. *Asian Journal of Agricultural Extension, Economics & Sociology*, *4*(3), 231–246.

Panagea, I. S., Berti, A., Čermak, P., Diels, J., Elsen, A., Kusá, H., ... & Wyseure, G. (2021). Soil water retention as affected by management induced changes of soil organic carbon: Analysis of long-term experiments in Europe. *Land*, *10*(12), 1362.

Parwada, C., & Chinyama, T. A. (2021). Land equivalent ratio of cowpea–sorghum relay intercrop as affected by different cattle manure application rates under smallholder farming system. *Frontiers in Sustainable Food Systems*, *5*, 778144.

Paustian, M., & Theuvsen, L. (2017). Adoption of precision agriculture technologies by German crop farmers. *Precision agriculture*, *18*(5), 701-716

Peoples, M. B., Brockwell, J., Herridge, D. F., Rochester, I. J., Alves, B. J. R., Urquiaga, S. & Sampet, C. (2009). The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis*, *48*(1-3), 1-17.

Pierre, J. F., Latournerie-Moreno, L., Garruña-Hernández, R., Jacobsen, K. L., Guevara-Hernández, F., Laboski, C. A., & Ruiz-Sánchez, E. (2022). Maize legume intercropping systems in southern Mexico: A review of benefits and challenges. *Ciência Rural*, *52*.

Pule-Meulenberg, F. (2018). Solutions for food security in Africa through sustainable soil fertility management of ecosystems under climate change: Proceedings of the 17th African Association for Biological Nitrogen Fixation Conference held in Gaborone Botswana 17–21 October 2016. *Symbiosis*, *75*(3), 165–166.

Purnomo, J., Kuswantoro, H., & Emerensiana Uge, P. (2024). Contribution of Agronomic and Rust Disease Intensity Traits to Yield Stability of Peanut Genotypes. *Nongye Jixie Xuebao/Transactions of the Chinese Society of Agricultural Machinery*, *55*(1).

Qazi, W., Raza, S. A., & Shah, N. (2018). Acceptance of e-book reading among higher education students in a developing country: the modified diffusion innovation theory. *International Journal of Business Information Systems*, *27*(2), 222-245.

Quaye, M. O., Sarkodie-Addo, J., Kennedy, A., Snr, P. A. P., & Kyere, C. G. (2020). Contribution of Okra (Abelmoschus esculentus L. Moench)–Cowpea (Vigna unguiculata L. Walp) Intercropping to Productivity of the System in Semi-deciduous Forest Zone of Ghana. *Asian Journal of Advances in Agricultural Research*, *13*(3), 10-20.

Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V., & Chatterjee, S. (2019). Climate change has likely already affected global food production. *PloS one*, *14*(5), e0217148.

Raza, S. A., Qazi, W., Khan, K. A., & Salam, J. (2021). Social isolation and acceptance of the learning management system (LMS) in the time of COVID-19 pandemic: an expansion of the UTAUT model. *Journal of Educational Computing Research*, *59*(2), 183-208.

Razafintsalama, H., Sauvadet, M., Trap, J., Autfray, P., Ripoche, A., & Becquer, T. (2021). Legume nitrogen fixation and symbioses in low-inputs rainfed rice rotations. *Sustainability, 13*(22), 12349.

Razvi, S.M., Khan, M.N., Bhat, M.A., Ahmad, M., Ganaie, S.A., Sheikh, F.A., Najeeb, S., F.A. Parry, F.A. (2018). Morphological variability and phylogenetic analysis in common bean (Phaseolus vulgaris L.). Legume Research. 41(2): 208-212.

Ren, Y., Zhang, L., Yan, M., Zhang, Y., Chen, Y., Palta, J. A., & Zhang, S. (2021). Effect of sowing proportion on above-and below-ground competition in maize–soybean intercrops. *Scientific Reports, 11*(1), 15760.

Renwick, L. L., Kimaro, A. A., Hafner, J. M., Rosenstock, T. S., & Gaudin, A. C. (2020). Maize-pigeonpea intercropping outperforms monocultures under drought. *Frontiers in Sustainable Food Systems, 4*, 562663.

Reza, S., Babul Akter, M., Rahman, M., Ali, I., & Bulbul Ahmed, M. (2022). Impact of Organic and Inorganic Fertilizers on Yield and Yield Contributing Characters of Mustard (Brassica napus L.). *Asian Journal of Soil Science and Plant Nutrition*, *8*(1), 27-34.

Rogers, E. M. (2003). *Diffusion of innovations*. Free Press; New York. 5th Edition ISBN-13.

Rola-Rubzen, M. F., Paris, T., Hawkins, J., & Sapkota, B. (2020). Improving gender participation in agricultural technology adoption in Asia: from rhetoric to practical action. *Applied Economic Perspectives and Policy, 42*(1), 113-125.

Rusinamhodzi, L., Nguyen, E., Marrou, H., Uzamushaka, S., & Corbeels, M. (2024). The influence of farm resources and management decisions on the severity of Striga infestation and maize productivity in western Kenya. *Weed Research*.

Sabo, M. U., Wailare, M. A., Aliyu, M., Jari, S., & Shuaibu, Y. M. (2013). Effect of NPK Fertilizer and Spacing on growth and yield of watermelon (Citrullus lanatus L.) in Kaltungo Local Government Area of Gombe State, Nigeria. *Scholarly Journal of Agricultural Science*, *3*(8), 325-330.

Sadiq, D., Nkama, I., & Esther, O. C. (2022). Effect of Processing on the Antinutrient Content of Extruded Snacks from Cocoyam–Bambara Groundnut Flour Blends. *Asian Food Science Journal*, *21*(9), 19-27.

Saha, K. K., Paul, S. K., & Sarkar, M. A. (2020). Influence of spacing of planting on the yield performance of some aromatic rice varieties in Boro Season. *Sustainability in Food and Agriculture*, *1*(1), 10-14.

Sahin, I. (2006). Detailed review of Roger's Diffusion of innovations theory and educational technology. *The Turkish Online Journal of Educational Technology*, *5*(2), 14–23.

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.

Sanguinetti, A., Karlin, B., & Ford, R. (2018). Understanding the path to smart home adoption: Segmenting and describing consumers across the innovation-decision process. *Energy research & social science*, *46*, 274-283.

Sarkar, S., Skalicky, M., Hossain, A., Brestic, M., Saha, S., Garai, S. & Brahmachari, K. (2020). Management of crop residues for improving input use efficiency and agricultural sustainability. *Sustainability*, *12*(23), 9808.

Scott, D., Scholes, J. D., Randrianjafizanaka, M. T., Randriamampianina, J. A., Autfray, P., & Freckleton, R. P. (2021). Identifying existing management practices in the control of Striga asiatica within rice–maize systems in mid-west Madagascar. *Ecology and Evolution*, *11*(19), 13579-13592.

Sellami, M. H., Pulvento, C., & Lavini, A. (2021). Selection of suitable genotypes of lentil (Lens culinaris Medik.) under rainfed conditions in south Italy using multi-trait stability index (MTSI). *Agronomy*, *11*(9), 1807.

Sennuga, S. O., Baines, R. N., Conway, J. S., & Angba, C. W. (2020). Awareness and adoption of good agricultural practices among smallholder farmers in relation to the adopted villages programme: The case study of Northern Nigeria. *Journal of Biology, Agriculture and Healthcare*, *10*(6), 34-49.

Séraphin, D. K., Léonce, N. G., Doudjo, S., & Emmanuel, A. N. (2024). Determination of essential mineral content of bambara groundnut (Vigna subterranea L.) produced in North of Côte d'Ivoire. *Journal of Food and Nutrition Research*, *12*(2), 98-104.

Sherry, L., & Gibson, D. (2002). The path to teacher leadership. *Contemporary Issues in Technology and Teacher Education*, *2*(2), 178–203.

Shi, R. Y., Liu, Z. D., Li, Y., Jiang, T., Xu, M., Li, J. Y., & Xu, R. K. (2019). Mechanisms for increasing soil resistance to acidification by long-term manure application. *Soil and Tillage Research*, *185*, 77-84

Sidibé, A., Meldrum, G., Coulibaly, H., Padulosi, S., Traore, I., Diawara, & Mbosso, C. (2020). Revitalizing cultivation and strengthening the seed systems of fonio and Bambara groundnut in Mali through a community biodiversity management approach. *Plant Genetic Resources*, *18*(2), 31-48.

Sidibé, A., Meldrum, G., Coulibaly, H., Padulosi, S., Traore, I., Diawara, G., & Mbosso, C. (2020). Revitalizing cultivation and strengthening the seed systems of fonio and Bambara groundnut in Mali through a community biodiversity management approach. *Plant Genetic Resources*, *18*(2), 31-48.

Singh, P. K., Barman, K., & Varshney, J. G. (2016). Adoption Behaviour of Vegetable Growers Towards Improved Technologies. *Indian Research Journal of Extension Education 11*(21) 62-65.

Smith A, Snapp S, Chikowo R, Thorne P, Bekunda M, Glover J. Measuring sustainable intensification in smallholder agroecosystems: a review. *Glob Food Sec.* (2017) 12:127–38. doi: 10.1016/j.gfs.2016.11.002

Suvedi, M., Ghimire, R., & Kaplowitz, M. (2017). Farmers' participation in extension programs and technology adoption in rural Nepal: a logistic regression analysis. *The Journal of Agricultural Education and Extension*, *23*(4), 351-371.

Tamiru, T., Worku, W., Mengesha, W., & Weyya, G. (2020). Response of Chickpea (Cicer aeritinum L.) Genotype to Intra and Inter Row Spacing at HuletegnaChoroko, Southern Ethiopia. *Ecology and Evolutionary Biology, 5*(4), 148.

Tan, L., Azam-Ali, S., Goh, E. V., Mustafa, M., Chai, H., Ho, K., ... & Massawe, F. (2020). Bambara groundnut: An underutilized leguminous crop for global food security and nutrition. *Frontiers in Nutrition*, *7,* 601496.

Tan, X. L., Azam-Ali, S., Goh, E. V., Mustafa, M., Chai, H. H., Ho, W. K., & Massawe, F. (2020). Bambara groundnut: An underutilized leguminous crop for global food security and nutrition. *Frontiers in Nutrition*, *7*, 601496.

Tang, W., Guo, H., Baskin, C., Xiong, W., Yang, C., Li, Z., & Sun, J. (2022). Effect of light intensity on morphology, photosynthesis and carbon metabolism of alfalfa (Medicago sativa) seedlings. *Plants*, *11*(13), 1688.

Tariq, A., Sardans, J., Peñuelas, J., Zhang, Z., Graciano, C., Zeng, F., & Pan, K. (2022). Intercropping of leguminous and non-leguminous desert plant species does not facilitate phosphorus mineralization and plant nutrition. *Cells*, *11*(6), 998.

Tehulie, N. S., & Yimam, K. M. (2021). Review on the Effect of Plant Population on Yield and Yield Components of Chickpea (Cicer arietinum L.). *Journal of Agricultural Research Pesticides and Biofertilizers*, *1*(5), 46-49.

Temegne, N. C., Foh, T. D. N., Taffouo, V. D., Wakem, G. A., & Youmbi, E. (2018a). Effect of mycorrhization and soluble phosphate on growth and phosphorus supply of voandzou [*vigna subterranea (L.) verdc*.]. *Legume Research*, *41*(6), 879–884.

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

Tessier, F. (2018). Determining the nitrogen content in (oxy) nitride materials. *Materials*, *11*(8), 1331.

Tey, Y. S., Li, E., Bruwer, J., Abdullah, A. M., Brindal, M., Radam, A., Darham, S. (2017). Factors influencing the adoption of sustainable agricultural practices in developing countries: A review. *Environmental Engineering and Management Journal*, Vol. 16, pp. 337–349.

Thilini, S. K., Pradheeban, L., & Nishanthan, K. (2019). Effect of Different Time of Earthing up on Growth and Yield Performances of Groundnut (Arachis hypogea L.) Varieties.

Tian, F., Zheng, Y., Zhang, T., Zhang, X., Mao, D., Sun, J., & Zhao, S. (2015). Statistical characteristics of environmental parameters for warm season short-duration heavy rainfall over central and eastern China. *Journal of Meteorological Research*, *29*(3), 370-384.

Tiroesele, B., Obopile, M., & Karabo, O. (2019). Insect diversity and population dynamics of natural enemies under sorghum–legume intercrops. *Transactions of the Royal Society of South Africa*, *74*(3), 258-267.

Toungos, D.T., A.A. Sajo and D.T. Gungula (2010). Effects ofP2O5 on the yield and yield components of Bambara groundnut (V. subterranea) in Yola Adamawa State, Nigeria. World. J. Fungal. Plant Biol., 1: 1-7.

Traore, K., & Zemadim, B. (2019). Improving crop-livestock productivity and household income through the use of contour bunding and agroforestry options.

Tshikukuvhe, L. D. (2017). *Exploration of indigeneous medicinal knowledge of Phonda in the Vhembe District*. Doctoral dissertation. University of Venda, South Africa.

Tsoata, E., Njock, S. R., Youmbi, E., & Nwaga, D. (2015). Early effects of water stress on some biochemical and mineral parameters of mycorrhizal *Vigna subterranea* (L.) Verdc. (Fabaceae) cultivated in Cameroon. *International Journal of Agronomy and Agricultural Research (IJAAR)*, *7*(2), 21–35.

Tsoata, E., Temegne Nono, C., & Youmbi, E. (2017). Analysis of early biochemical criterion to screen four Fabaceae plants for their tolerance to drought stress. *International Journal of Current Research*, *9*(1), 44568–44575.

Umeugokwe, C. P., Ugwu, V. U., Umeugochukwu, O. P., Uzoh, I. M., Obalum, S. E., Ddamulira, G., ... & Alenoma, G. (2021). Soil fertility indices of tropical loamy sand as influenced by bambara groundnut variety, plant spacing and fertilizer type. *Agro-Science*, *20*(1), 65-71.

Uzoma, K. C., Omeke, J. O., Akpan, J. F., & Chukwu, G. O. (2021). Effects of Tillage and Bradyrhizobium Inoculation in Soybean/Maize Intercrop on Microbial Biomass and Water-Soluble Carbon in Samaru, Nigeria. *Nigeria Agricultural Journal*, *52*(3), 172-178.

Valerie, P., & Luvembe, S. W. (2016). Influence of farmers' socio-economic characteristics on adoption of Bambara Nut Production in Western Kenya. *Asian Journal of Agricultural Extension, Economics & Sociology*, 14(1) 1-10.

Valombola JS, Akundabweni LM, Awala SK, Hove K (2019). Agronomic and morphological diversity of Bambara groundnut (Vigna subterranea (L) Verdc.) accessions in North-Central Namibia. Wewitschia Int. J. Agric. Sci. 1:88-99.

Vanlauwe, B., Hungria, M., Kanampiu, F., & Giller, K. E. (2019). The role of legumes in the sustainable intensification of African smallholder agriculture: Lessons learnt and challenges for the future. *Agriculture, ecosystems & environment*, *284*, 106583.

Vanslembrouck, I., Van Huylenbroeck, G., & Verbeke, W. (2002). Determinants of the willingness of Belgian farmers to participate in agri-environmental measures. *Journal of agricultural economics*, *53*(3), 489-511.

Varble, S., Secchi, S., & Druschke, C. G., (2016). An examination of growing trends in land tenure and conservation practice adoption: Results from a farmer survey in Iowa. *Environmental management*, *57*(2), 318-330.

Verde, B. S., Danga, B. O., & Mugwe, J. N. (2014). Soil microbial biomass changes with application of organic and inorganic in acid soil in Embu County, Kenya. *Scholarly Journal of Agricultural Science*, *4*(1), 27-31.

Verkaart, S., Mausch, K., Claessens, L., & Giller, K. E. (2019). A recipe for success? Learning from the rapid adoption of improved chickpea varieties in Ethiopia. *International journal of agricultural sustainability*, *17*(1), 34-48.

Vogel, J., Rivoire, P., Deidda, C., Rahimi, L., Sauter, C. A., Tschumi, E., & Zscheischler, J. (2020). Identifying meteorological drivers of extreme impacts: an application to simulated crop yields. *Earth System Dynamics Discussions*, *2020*, 1-27.

Wang, Q., Bai, W., Sun, Z., Zhang, D., Zhang, Y., Wang, R., & Zhang, L. (2021). Does reduced intraspecific competition of the dominant species in intercrops allow for a higher population density?. *Food and Energy Security*, *10*(2), 285-298.

Wang, W., Li, M. Y., Gong, D. S., Zhou, R., Khan, A., Zhu, Y., & Xiong, Y. C. (2022). Water use of intercropped species: Maize-soybean, soybean-wheat and wheat-maize. *Agricultural Water Management*, *269*, 107690.

Wanjue, N. A., Kingori, G. G., & Mahugu, M. M. (2023). Effect of Rate and Time of Phosphorous Application and Planting Density on Yield and Net Benefit of Groundnut (Arachis hypogaea). *International Journal of Plant & Soil Science*, *35*(14), 94-108.

Wasula, S., Wakhungu, J., & Palapala, V. (2014). Farmers' Perceptions On Adoption of Bambara Nut Production As A Food Security Crop In Kakamega County, Kenya *International Journal of Disaster Management and Risk Reduction*. *6*.

Woo, J., Chung, S., Lee, C. Y., & Huh, S. Y. (2019). Willingness to participate in community-based renewable energy projects: A contingent valuation study in South Korea. *Renewable and Sustainable Energy Reviews*, *112,* 643-652.

Xin, L. I. U., WANG, W. X., Xiang, L. I. N., GU, S. B., & Dong, W. A. N. G. (2020). The effects of intraspecific competition and light transmission within the canopy on wheat yield in a wide-precision planting pattern. *Journal of Integrative Agriculture*, *19*(6), 1577-1585.

Xulu, S. E., Gerrano, A. S., & Mavengahama, S. (2024). Assessment of morphological and chlorophyll content traits in Bambara groundnut (Vigna subterannea [verdc L.]). *Journal of Underutilised Crops Research*, *3*(1), 6.

Yadav, S., Modi, P., Dave, A., Vijapura, A., Patel, D., & Patel, M. (2020). Effect of abiotic stress on crops. *Sustainable crop production*, *3*.

Yakubu, H., Kwari, J. D., & Sandabe, M. K. (2010). Effect of phosphorus fertilizer on nitrogen fixation by some grain legume varieties in Sudano–Sahelian Zone of North Eastern Nigeria. *Nigerian journal of Basic and Applied sciences*, *18*(1), 44-49.

Yin, S., Wang, Y., Zhibiao Nan, Z. (2018). Genetic diversity studies of alfalfa germplasm (Medicago sativa L. subsp. sativa) of United States origin using microsatellite analysis. Legume Research. 41(2): 202-207.

Yu, Y. (2016). *Crop yields in intercropping: meta-analysis and virtual plant modelling* (Doctoral dissertation, Wageningen University and Research).

Zakaria, A., Azumah, S. B., Appiah-Twumasi, M., & Dagunga, G. (2020). Adoption of climate-smart agricultural practices among farm households in Ghana: The role of farmer participation in training programmes. *Technology in Society*, *63*, 101338.

Zenabou, N., Martin, F., Ernest, P., Bassiaka, O., Claude, S., Siegfried, D., (2014). Agro-morphological variability in twelve BambaraBambara groundnut [Vigna subterranean (L.) Verdc.] accessions in Cameroon. Sciences, Technologies et Développement. 16: 38-45

Zeven, A. C. (1998). Landraces: A review of definitions and classifications. *Euphytica*, 104(2), 127-139.

Zhang, Z., Chattha, M. S., Ahmed, S., Liu, J., Liu, A., Yang, L., & Yang, G. (2021). Nitrogen reduction in high plant density cotton is feasible due to quicker biomass accumulation. *Industrial Crops and Products*, *172*, 114070.

Zhou, Q., Li, X., Lin, Y., Yang, C., Tang, W., Wu, S., & Lou, W. (2019). Effects of copper ions on removal of nutrients from swine wastewater and on release of dissolved organic matter in duckweed systems. *Water research*, *158*, 171-181.

APPENDICES

Appendix 1: Study questionnaire

Study questionnaire on the willingness of smallholder farmers to adopt the best agronomic practices of Bambara groundnut

We express our gratitude for participating in implementation of best agronomic practices of Bambara groundnut production. We therefore request that you share with us your experience with the best practices of Bambara groundnut production. The information shared will assist in further dissemination of the study findings for enhanced adoption of Bambara groundnut. The data shared was handled with utmost confidentiality and personal details will not be published anywhere.

Date of interview…../…../2020 Sub-county……………….....................

Location………………………………… Phone number………………………….

Section 1: Demographic Characteristics

a) Gender of the farmer Male [ ] Female [ ]
b) Age of the farmer 18-30 [ ] 31-50 [ ] 51 and above [ ]
c) Gender Male [ ] Female[ ]
d) Level of education of the farmer Non formal [ ] Primary [ ] Secondary [ ] Tertiary [ ] Other specify…………………
e) How many years have you been a farmer? Less than 10 years [ ] 10-20 years [ ] above 20 years [ ]
f) What is your household size? …………………………………

Section 2: Farm Characteristics

a) What is the size of your farm in acres? _________________
b) Do you practice crop farming? 1=YES 0=NO
c) If yes, for question “b” above, what are your main food crops?
    1. Maize
    2. Beans
    3. Sorghum
    4. Millet
    5. Pigeon Peas
    6. Green grams
    7. Horticultural Crops
    8. Other (Specify) __________________________
d) Which cropping system do you practice in your farm?
    1. Mono cropping

    2. Intercropping
    3. Mixed cropping

e) Do you produce enough of the main crop for household consumption? 1=YES; 0=NO

f) If no, for question “e” above, what causes the deficit?
    1. Large family size
    2. Small land size
    3. Crop Failure
    4. Lack of funds
    5. Lack of labour
    6. Other (Specify) ___________________________

g) How often do you suffer crop failure in your farm?
    1. Once a year
    2. Twice a year
    3. Once in five years

h) According to you, what are the main causes of crop failure in your area?
    1. Drought
    2. Floods
    3. Lack of farm inputs
    4. Poor farming practices
    5. Cost of adopting improved technologies
    6. Other (Specify) ___________________________

Section 3: Level of Awareness of Bambara Groundnuts Production

a) Had you ever heard of Bambara groundnut before your participation in this study? 1=YES; 0=NO

b) If yes for question “a” above, have you ever planted Bambara groundnut? 1=YES; 0=NO

c) If yes for question “b” above, please provide the following information:
    i) When did you last plant Bambara groundnut?
    ii) What was your source of seed?
    iii) Quantity planted (kg)?
    iv) Acres Planted?
    v) Spacing Used?
    vi) Cropping system used 1. Pure stand? 2. Intercropping?
    vii) Quantity harvested (kg)?

Section 3: Indicators of Adoption of Bambara Groundnuts Production

a) How do you rate the agronomic potential of Bambara groundnut in the region?
   1. Very High
   2. High
   3. Average
   4. Low
   5. Very Low

b) Are you willing to start/continue production of Bambara groundnut in your farm? 1=YES; 0=NO

c) If no for question “b” above, please give reasons

…………………………………………………………………………………………

…………………………………………………………………………………………

d) If yes for question “b” above, which cropping system are you willing to adopt?
   1. Pure Stand
   2. Intercropping with legume

   Please give reasons to support your choice

   …………………………………………………………………………………………

   …………………………………………………………………………………………

   If your choice is intercropping with the legume cropping system, which practice are you willing to adopt?

   1. Intercropping with legume residues removed after harvest
   2. Intercropping with legume residues incorporated in the soil

   Please give reasons to support your choice

   …………………………………………………………………………………………

   …………………………………………………………………………………………

e) What are your main sources of non-farm income?
   1. Employment
   2. Business
   3. Other (Specify) ____________________________

f) Do you think this off-farm income may affect the decision to adopt Bambara groundnut production? 1 = YES; 0 = NO

g) If yes, for question “g” above, how?

…………………………………………………………………………………………

…………………………………………………………………………………………

h) What other factors do you think may prevent you from adopting Bambara groundnut production?

…………………………………………………………………………………………

…………………………………………………………………………………………

i) What kind of support would you currently require to enable you effectively practice Bambara groundnut production?

………………………………………………………………………………………………

………………………………………………………………………………………………

We are grateful for your time and honest cooperation in answering our questions. It's our hope that some of the results were useful to you and the community in addressing food productivity in dry lands.

THANK YOU

Appendix 2: Weather data of Embu County

MET Station	YEAR	MM	PRECIP	TMPMAX	TMPMIN	RELHUM	RELHUM12	WNDDIR	WNDSPD	EVAPPN1
EMBU	2019	1	46.3	mis	13.6	67.3	52.5	82.6	3.5	5.3
EMBU	2019	2	21.6	mis	13.9	69.4	43.4	61.6	4	5.7
EMBU	2019	3	22.4	mis	14.3	65.5	37.7	69.1	3.3	6.6
EMBU	2019	4	189.5	mis	16.5	76	45.2	77.9	2.7	5.4
EMBU	2019	5	141.5	19.5	16.1	80.4	58.8	80.8	2	3.5
EMBU	2019	6	23.5	22.7	15.2	82	66	68.2	1.3	2.1
EMBU	2019	7	3.7	23.7	14.2	78	53	76.9	1.6	2.8
EMBU	2019	8	20	24.4	13.6	78.4	50.1	86.4	1.9	3
EMBU	2019	9	11.6	26	14.3	74.5	44.1	91.6	2	3.8
EMBU	2019	10	442.9	25.5	15.3	83.1	57.2	84	2.3	4.4
EMBU	2019	11	260.1	24.9	15.2	78.7	63.8	74.5	2.8	4
EMBU	2019	12	214	24.7	14.4	76.5	68.1	58.9	2.6	3.6
EMBU	2020	1	74.2	25.2	14.8	75.4	63.9	69.1	3	3.9
EMBU	2020	2	60	26.6	14.2	75.3	56.1	60.8	2.7	4.7
EMBU	2020	3	195.6	26.6	15.9	80.3	61.6	68.1	2.3	4.5
EMBU	2020	4	351.1	25.9	15.4	81	58.7	79.1	2.3	3.4
EMBU	2020	5	229.4	25.5	15	79.3	59.7	97.2	2	3.6
EMBU	2020	6	27.2	23.4	13.4	81	60.3	77.8	1.5	2.8
EMBU	2020	7	21	22.7	12.6	80.5	57.9	82.9	1.5	2.4
EMBU	2020	8	41	23.7	12.8	80.2	55.2	86	1.7	2.8
EMBU	2020	9	44.1	25	13.6	79.3	52.4	83.5	2	3.5
EMBU	2020	10	272.9	26.5	14.2	75	48.9	98.4	2.4	4.7
EMBU	2020	11	282.7	24.9	13.8	78.2	61.9	75.9	3	3.9
EMBU	2020	12	92.8	25.2	11.9	69.2	58.9	87	4.2	4.4

Source: Kenya Meteorological department