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EFFECT OF TILLAGE METHODS AND NUTRIENT APPLICATION LEVELS ON SOIL PROPERTIES AND SOGHUM AND GREENGRAM YIELDS IN SIAKAGO, EMBU COUNTY, KENYA

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DECLARATION

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

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DEDICATION

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ABBREVIATIONS AND ACRONYMS

AAS	Atomic Absorption Spectrophotometer
ANOVA	Analysis of Variance
ASALs	Arid and Semi-Arid Lands
ATDC	Agricultural Technology Development Centre
CEC	Cation exchange capacity
DAP	Di-ammonium phosphate
EC	Electrical conductivity
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Statistics
FF	Full fertilizer
FM	Full manure
FYM	Farm yard manure
GDP	Gross Domestic Product
HM	Half manure
HMHF	Half Manure Half Fertilizer
LSD	Least significant difference
MOA-ERA	Ministry of Agriculture- Economic Review of Agriculture
NARL	National Agricultural Research Laboratories
SOM	Soil organic matter
SOP	Standard Operating procedure
SSA	Sub-Saharan Africa
TOC	Total Organic Carbon
USAID	United States Agency for International Development

ABSTRACT

Declining soil fertility is a significant constraint to sorghum and green gram yields for smallholder farmers in semi-arid regions of Kenya. This research was carried out in Siakago, Embu County, Kenya, with the aim of assessing the efficacy of different tillage methods and inorganic and organic fertilizers for sorghum and green gram production. The research was performed for four consecutive seasons from October 2018 to February 2021 at the Agricultural Technology Development Centre, Siakago in Mbeere North sub-County. In the study, there were a total of 24 different treatments using a randomized full block design with three replicates. The treatments comprised of two different types of tilling, namely conventional and tied ridges, three cropping systems (sole-green grams, sole-sorghum, and green grams + sorghum intercrops) and four soil fertility input regimes (no inputs), (60 kg DAP ha^{-1}), (5.0 t ha^{-1} manure) and a combination of manure and inorganic fertilizer as (2.5 t ha^{-1} + 30 kg DAP ha^{-1}). Soil properties, including organic carbon, nitrogen, phosphorus, potassium, calcium, magnesium, manganese, iron, zinc, and copper, were analyzed before and after the experiment. Crop parameters, such as days to 50% flowering, plant height, leaf chlorophyll content, biomass, and grain yields, were also measured. The treatment effects were analyzed using ANOVA, and a significance level of $p \leq 0.05$ was used to differentiate the treatment means using post hoc Turkey’s HSD test. Differences in treatment means were analyzed using Fisher's test for the test with the least significant difference, which was performed at a significance level of $p \leq 0.05$. The results showed that tied ridge tillage practice significantly increased exchangeable phosphorus and magnesium contents. The green gram cropping system registered higher but insignificant nutrient status compared to sole sorghum or sorghum-green gram cropping systems. Organic-based fertility inputs positively affected soil organic carbon, although these increases were not statistically significant. Soil inputs significantly influenced soil carbon concentrations, with the lowest values observed in the control treatment. The study found that sorghum supplied with full-rate inorganic fertilizer had greener leaves and produced 75% higher grain than in the control. The pure farmyard manure treatment produced 45% more grain compared to the control. Tied ridges did not significantly increase yields $p \leq 0.05$. Similar trends were observed in green grams. This research emphasizes the significance of applying soil conservation techniques, such as tied-ridging, in conjunction with organic input applications, to improve the availability of multiple nutrients for better crop performance and human nutrition in dryland farming systems.

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

The agriculture sector in Kenya is a significant contributor to the country's economy, accounting for approximately 33% of the gross domestic product, with over 75% of the population deriving their livelihood directly from agricultural activities (FAO 2022). However, agricultural productivity in Eastern Kenya faces multifaceted challenges such as reduced soil fertility, high population density, and high opportunity costs related to limited land use (Okeyo *et al.* 2020). On top of these challenges, they also face land degradation problems and insufficient soil management practices, leading to soil nutrient depletion and diminished crop yields (Mairura *et al.* 2022). Embu County, is categorized by the FAO (2022), as a "stressed" food security zone which is primarily caused by the lack of proper soil management practices coupled with extensive soil nutrient depletion, a pervasive issue across agricultural systems in Sub-Saharan Africa (Kugedera *et al.* 2022).

According to Micheni (2015), inadequate soil management, ineffective tillage systems, and insufficient fertilizer application are significant contributors to increased food insecurity in the Sub-Saharan African region, particularly in the Eastern province of Kenya's central highlands. To enhance soil fertility and crop yields, judicious fertilizer usage tailored to specific soil conditions is essential (Mondal *et al.* 2021). However, optimizing fertilizer application requires farmers to have a thorough understanding of soil properties and dynamics.

Agriculture not only plays a vital economic role in Kenya but also faces the challenge of declining land fertility, which exacerbates malnutrition and poverty among rural populations in the Eastern Kenya (Okeyo *et al.* 2020). The Mbeere sub-Counties, heavily reliant on short rains for crop production, are experiencing a concerning trend of deteriorating dietary diversity and food consumption rates, as evidenced by a 10% increase in households with poor food consumption scores in 2016 (Isaboke *et al.* 2016).

Tillage, an essential agricultural practice involving soil preparation through mechanical interventions such as digging and overturning, has been a cornerstone of agricultural practices for centuries (Shakoor *et al.* 2021). Conventional tillage, or intensive tillage system, involves using machinery to break up the soil to about 8-10 inches deep, followed by the incorporation of fertilizers, pesticides, and other amendments. However, conventional tillage can lead to soil erosion and reduced soil organic matter, which can negatively impact soil fertility and crop yields (Musafiri *et al.* 2023). This method has been the standard approach for soil preparation for many years, but it has recently faced criticism due to its negative environmental consequences, including the loss of organic soil matter, soil erosion, and soil structure degradation. In contrast, conservation tillage systems, which minimize soil disturbance, can help preserve soil structure, increase soil organic matter, and improve soil health (Kisaka *et al.* 2023). For instance, tied ridges/reduced-tillage systems, also known as conservation tillage, is a more recent approach to soil preparation that has gained popularity in recent decades. Although this approach still involves some degree of soil disturbance, it is designed to minimize soil disruption and promote soil health (Mondal *et al.* 2021). By combining it with other agricultural practices such as crop rotation and pest management, this method has been shown to yield the best results.

One of the most significant differences between conventional tillage and tied ridges is the level of soil disturbance. Conventional tillage involves deep plowing, which can weaken soil structure and lead to erosion. In contrast, tied ridges generally involve shallow tillage or no-till practices, which help to preserve soil structure and reduce erosion. This reduced soil disturbance also helps to foster soil organisms, such as earthworms and microorganisms, which are essential for soil health. Another key difference between conventional tillage and tied ridges is in how the two systems control weeds. Conventional tillage frequently relies on herbicides to control weeds, which can harm beneficial insects and microorganisms (Okeyo *et al.* 2020). In contrast, tied ridges implement cover cropping to suppress weeds and improve soil health. These cover crops can also provide additional benefits, such as improving soil structure and providing habitat for beneficial insects.

Tied ridges and conventional tillage differ in their effects on soil moisture. Conventional tillage can result in soil compaction, which reduces soil water infiltration and increases runoff. On the other hand, tied ridges rely on cover crops to prevent soil erosion, which promotes water infiltration, and strengthens the soil structure. In addition to these differences, tied ridges offer several advantages over conventional tillage (Mandumbu *et al*. 2020). For instance, tied ridges can reduce soil erosion by up to 90% compared to conventional tillage, improve soil health by promoting soil bio ta and enhancing soil structure, and minimize the need for herbicides and other chemicals, leading to a more sustainable and eco-friendly approach to agriculture.

Although tied ridges provide numerous benefits, they come with some challenges. For instance, tied ridges might require more labor and equipment than conventional tillage, especially during the initial stages of adoption. Additionally, tied ridges may necessitate careful management of soil moisture and nutrients, as the reduced soil disturbance can lead to changes in soil chemistry (Mak-Mensah *et al.* 2022). Therefore, tied ridges represent a more sustainable and environmentally-friendly approach to soil preparation than conventional tillage. While both methods have their advantages and disadvantages, tied ridges provide a comprehensive approach to agriculture that enhances soil health, reduces erosion, and minimizes the use of chemicals. The rapid global population growth puts more pressure on the need for sound agricultural practices, making tied ridges a key player to supplement other agricultural practices and ensure sustainable agriculture.

In Embu County, Kenya, small-scale farmers face the main challenges of soil degradation and low crop productivity. The use of fertilizer in the region is constrained by unfavorable price ratios and financial limitations. For instance, farmers prioritize cash crops over food crops due to the high cost of fertilizer relative to crop prices. Additionally, there is a scarcity of records on the impact of tillage practices on crop yields, particularly for sorghum and green grams in Rhodic Ferralsols.

Conventional tillage has been the dominant method of soil preparation in Embu County, involving deep plowing and the use of herbicides and other chemicals. In contrast, tied ridges or conservation tillage involves shallow tillage or no-till practices, which help to reduce soil erosion and preserve soil structure. This approach also utilizes cover crops to suppress weeds and improve soil health.

Organic and inorganic fertilizers play a significant role in soil fertility management in Embu County. While organic fertilizers, such as compost and manure, have low nutritional value, they require significant labor to prepare, transport, and apply. Inorganic fertilizers, on the other hand, have high nutritional value but can have an adverse environmental impact, including being an agent of water pollution and soil contamination. Therefore, it is important to carefully consider the benefits and drawbacks of both types of fertilizers in order to make informed decisions about soil fertility management. The economic and environmental sustainability of various fertilizer application techniques is crucial for farmers to weigh, as they must balance improving soil fertility while minimizing environmental consequences (Tian *et al.* 2022).

Therefore, this research aims to evaluate the effects of conventional tillage, tied ridges, and organic and inorganic fertilizers on crop yields in Embu County. Specifically, the study will investigate the effects of different tillage methods on soil structure and fertility and the impact of organic and inorganic fertilizers on crop yields. Additionally, the study will examine the environmental sustainability and economic viability of various fertilizer application strategies. The findings will provide valuable insights to small-scale farmers in Embu County, enabling them to make informed decisions regarding fertilizer application and tillage practices that enhance soil fertility and crop productivity while minimizing environmental impacts. The research will focus on sorghum and green gram, two significant crops in Embu County, and will be conducted in Rhodic Ferralsols, a prevalent soil type in the region. The study will employ a randomized complete block design with three replicates of each treatment, including conventional tillage with inorganic fertilizer, tied ridges with organic fertilizer, and tied ridges with inorganic fertilizer. Soil and plant analyses will be conducted to assess the effects of different treatments on soil properties and crop yields. The results of this study will greatly benefit small-scale farmers in Embu County, allowing them to make informed decisions about fertilizer application and tillage practices that improve soil fertility and crop productivity while minimizing environmental impacts. Additionally, the study will contribute to the development of sustainable agricultural practices in Embu County, which is essential for enhancing food security measures and increasing the income of small-scale farmers in the region.

1.2 Problem Statement

In Embu County, Kenya, small-scale farmers face significant challenges in increasing their crop productivity due to declining soil fertility. These farmers often struggle to afford fertilizers, and some are limited by the unfavorable crop to fertilizer price ratio. Additionally, farmers may prioritize cash crops over food crops due to financial constraints. The impact of tillage practices on crop yields, particularly for sorghum and green grams in Rhodic Ferralsols, is not well understood, partly due to the scarcity of available records (Mairura *et al.* 2022). Conventional tillage, involving deep plowing and the use of herbicides and other chemicals, has been the dominant method of soil preparation in Embu County. This approach promises substantial increases in farm produce, but it has been criticized for its negative environmental impacts, including soil erosion and the loss of soil organic matter.

Another critical aspect of soil fertility management in Embu County is the use of organic and inorganic fertilizers. Organic fertilizers, such as compost manure, require significant labor to prepare, transport, and apply and have low nutritional value. Inorganic fertilizers, on the other hand, are highly nutritious but can have negative environmental impacts, such as water pollution and soil contamination. This study aims to investigate the effects of conventional tillage, tied ridges, and organic and inorganic fertilizers on crop yields in Embu County. Specifically, the study examined the effects of different tillage practices on soil structure and fertility and the impact of organic and inorganic fertilizers on crop yields. The study also assessed the environmental sustainability and economic viability of different fertilizer application strategies. The findings of this study provide valuable insights for small-scale farmers in Embu County, enabling them to make informed decisions about fertilizer application and tillage practices that improve soil fertility and crop productivity while minimizing environmental impacts.

1.3 Justification of the Study

The importance of fertilizer application and tillage in affecting soil characteristics and crop productivity justifies this study. Food insecurity and poverty are among the main issues raised by small-scale farmers in Embu County, Kenya, due to soil degradation and low crop productivity. The use of fertilizers is limited by unsustainable crop to fertilizer price ratios and financial constraints, leading farmers to prioritize cash crops over food crops. Additionally, the effects of tillage practices on soil properties and crop yields in the region are not well understood, making this study necessary. Conventional tillage, which involves deep plowing and the use of herbicides and other chemicals, has been criticized for its negative environmental impacts, such as soil erosion, degradation of soil structure, and loss of soil organic matter. In contrast, tied ridges or conservation tillage involves shallow tillage or no-till practices, which help to preserve soil structure and reduce erosion. This approach often includes the use of cover crops, which help to suppress weeds and improve soil health.

This study aims to explore the effectiveness of organic and inorganic fertilizers in enhancing soil fertility and crop productivity, ultimately empowering farmers to optimize their yields and improve the sustainability of their agricultural practices. Organic fertilizers, such as compost and manure, have low nutritional value but require significant labor to prepare, transport, and apply. Inorganic fertilizers, on the other hand, have high nutritional value but can have negative environmental impacts, such as water pollution and soil contamination (Mairura *et al.* 2022). The economic and environmental sustainability of different fertilizer application strategies is also a critical consideration, as farmers must balance the need to improve soil fertility with the need to minimize environmental impacts. The study also contributes to the formulation of sustainable agriculture practices in Embu County, which is critical for enhanced food security and elevating living standards of small-scale farmers in the region. The findings of this study also provide guidance to small-scale farmers in Embu County, enabling them to make informed decisions about fertilizer application and tillage practices that improve soil fertility and crop productivity while minimizing environmental impacts.

1.4 Objectives

1.4.1 Broad objective

To evaluate how the tillage practices and how the use of organic and inorganic fertilizers affects the soil properties and the yields of both sorghum and green gram in Siakago, Embu County, Kenya.

1.4.2. Specific objectives

i. To determine the effect of conventional tillage and tied ridges on selected soil properties in Siakago, Embu County

ii. To evaluate the effect of conventional tillage and tied ridges on sorghum and green gram production in Siakago, Embu County

iii. To assess the effects of organic and inorganic fertilizers on selected soil properties in Siakago, Embu County

iv. To assess the effects of organic and inorganic fertilizers on sorghum and green grams yields in Siakago, Embu County

1.5 Research Hypotheses

1. Conventional and tied tillage practices have no significant effect on selected soil properties in Siakago, Embu County
2. Conventional and tied ridges tillage have no significant effect on sorghum and green gram production in Siakago area of Embu County
3. Inorganic and organic fertilizers have no significant effect on selected soil properties in Siakago, Embu County.
4. Inorganic and organic fertilizers have no significant effect on sorghum and green gram production in Siakago area of Embu County

CHAPTER TWO

LITERATURE REVIEW

2.1 Tillage Systems

Tillage is a crucial agricultural technique that involves mechanically preparing the soil for planting by breaking up and aerating the soil structure, allowing for optimal seed placement and root growth. This process involves various techniques, including digging, overturning, and stirring, as described by Zhang *et al.* (2023). Tillage is often combined with other agricultural methods, such as crop rotation and soil covering, as highlighted by Shah *et al*. (2021). The main purpose of tillage is to improve the soil environment, thereby promoting crop growth and reducing the risk of mineral loss.
Tillage practices can be categorized based on the level of surface remains that are left on the soil. Common tillage methods include zero-till, minimum-till, conventional, and tied ridges. Zero-till farming, for instance, involves planting crops without disturbing the soil, while minimum-till farming involves minimal disturbance of the soil (Kumar *et al.*, 2020). Conventional tillage, on the other hand, involves deeper and more extensive tillage, often resulting in greater soil disturbance. Tied ridges, a type of conservation tillage, involve creating narrow ridges in the soil to help retain more soil moisture and minimize soil erosion.

The preferred tillage method to be used is determined by factors such as the soil type, climate, and crop requirements. For instance, in areas with heavy rainfall or high soil erosion risk, the tied ridges conservation tillage method may be more effective in reduction of soil erosion as well as improvement of soil moisture. In contrast, in areas with dry or sandy soils, conventional tillage may be more effective in improving soil structure and promoting crop growth. Several recent researches have been involved in expressing the importance of tillage in facilitating soil health and reducing soil erosion. For instance, a study by Ferdous *et al*. (2022) found that conventional tillage improved the soil structure while increasing crop yields. Another study by Wang *et al*. (2020) discovered that tied ridges reduced soil erosion and improve soil moisture. These findings emphasize the need for a balanced approach to tillage, taking into account the specific soil type, climate, and crop requirements.

Research has it that tillage, when implemented correctly, will facilitate the conservation of the environment especially reducing the overall impact of agriculture. For instance, Liu *et al*. (2022) found that no-till or reduced-till farming reduced greenhouse gas emissions and improved soil carbon separation. Another study by Zhang *et al.* (2018) found that conservation tillage can be used to improve soil fertility while also reducing soil erosion. Therefore, tillage is a critical component of modern agriculture, and its importance cannot be overstated. The benefits of tillage extend beyond the farm gate, with implications for the environment and society as a whole. Tillage, for instance, can aid in reduction of soil erosion, which can lead to increased sedimentation in waterways and decreased water quality. Implementing tillage practice can have a positive environmental impact and health impact as it will minimize the usage of synthetic fertilizers and pesticides.

Furthermore, tillage can also have a great impact on the overall climate change. Tillage, for example, can aid in the soil's sequestration of carbon, lowering greenhouse gas emissions and lessening the effects of climate change. Additionally, tillage can help to improve soil health, which can help to bolster agricultural systems' ability to withstand climate change (Shah *et al*. 2021). Therefore, tillage is a critical component of modern agriculture, with implications for soil health, crop growth, and environmental sustainability. By understanding the different tillage methods and their benefits, Farmers are able to decide with knowledge what course of action is appropriate for their particular circumstances.

2.1.1 Soil properties under tied ridge and conventional tillage

Soil properties play a crucial role in determining the effectiveness of tillage methods. Tied ridge tillage, for instance, has been shown to improve soil water retention and reduce runoff. This is achieved through the creation of ridges that slow down the flow of rainfall, allowing for increased infiltration and soil water storage (Mak-Mensah *et al.* 2022). A study by Vanlauwe *et al.* (2015) found that ridge tillage facilitated faster drying up of the seed area, resulting in improved soil moisture and increased crop yields.

The introduction of tied ridges has been found to have a significant impact on soil properties. According to Njau (2017), the introduction of tied ridges caused a significant reduction in runoff and soil loss. Tied ridges retain runoff, allowing for more time for infiltration and increased soil water storage. Rainwater can be retained for a longer period on open furrows, leading to better retention of moisture and improved crop yields (Ferdous *et al.* 2022). This method works best in locations with light to moderate rainfall, well-drained soil, and mild slopes.

Conventional tillage, on the other hand, can have a significant impact on soil properties. According to Wawire *et al.* (2021), conventional tillage changes various features of the soil, including its physical and chemical properties. Changes in soil occur due to variables such as its composition and type. For instance, a soil's organic composition can explain why it has distinctive chemical properties. Tillage impacts soil quality, particularly for crops like sorghum and green gram, which rely heavily on crop residue management (Karami *et al.* 2012). In crop production, conventional tillage affects soil aggregation, which affects the amount of soil moisture, which is crucial in arid and semi-arid areas. Conventional tillage in Arenosols, Luvisols, and Lixisols is associated with decreased soil organic matter, causing soil degradation and loss of soil components (Mansour *et al.* 2021).

Recent studies have highlighted the importance of considering soil properties when implementing tillage methods. For example, a study by Wang *et al.* (2020) found that soil properties play a critical role in determining the effectiveness of conservation tillage. Another study by Zhang *et al.* (2018) found that soil properties can affect the effectiveness of no-till farming.

2.1.2 Sorghum and green gram yields under tied ridges and conventional tillage

As of 2022, Kenya produced 135,000 metric tonnes of sorghum. In comparison to other countries in the sorghum production such as Nigeria and Ethiopia, Kenya performs below par (FAO, 2022). The cereal is ground to flour and used to make porridge (*ugali).* Mak-Mensah *et al.* (2022) found out that behind maize, wheat, barley, sorghum is the fifth most consumed cereal throughout the world. It can out-yield most cereals in hot and dry climates and thrives on a variety of poor soils with limited rainfall. The agro-ecological zones of Kenya are where it really shines (Nosheen *et al*. 2021). This crop is drought-resistant and does well in dryer parts of the country such as lower Embu.

Sorghum in Kenya is mainly produced in the country's southwestern and south-central regions, specifically the Nyanza, Eastern, Rift Valley and the Western regions, which produced 40%, 44%, 7.2%, and 8.8% respectively of the country's total sorghum output in 2011 accordingly. Mwadalu (2013) estimates that 99 percent of the country's sorghum comes from these areas. A total of 1.5 million more bags of sorghum were consumed in Kenya in 2008 than in 2004, as reported by USAID (2010). Populations of dry and Semi-Arid areas have apparently begun to appreciate sorghum for its usefulness as a food security crop, as seen by the rise in its consumption. Some challenges of sorghum farming include adverse weather conditions, bird damage and lack of market. Sorghum has a well-established rooting system and the potential to broaden its leaves during hot weather (Mansour *et al.* 2021).

Tied ridges have been found to increase yield of maize intercropped with green gram from 1.10 to 1.15 t/ha in semiarid areas of northern Tanzania (Njau, 2017). Kugedera *et al.* (2018) found that when comparing sorghum grown using conventional tillage methods to sorghum cultivated using tied ridges, the latter produced enhanced harvests of grains and stovers by 3.7% and 10.4%, respectively. This may be because improved root development is accompanied by increased sorghum growth because of the increased amount of water in the soil from the rain water harvesting systems. This evidence was supported by Sullivan *et al.* (2020) who concluded that the harvests of sorghum were enhanced with the use of knotted ridges. In Kenya, Mugo *et al.* (2020) found that linked ridges combined with fertilizer management resulted in higher crop yields than conventional tillage plus amendments. When comparing the yield of sorghum planted flat and when planted using the tied-ridging method, Mairura *et al.* (2022) showed that the latter resulted in a 62% increase.

Kugedera *et al.* (2018) found that even with sound farming practices with fertilizers, conventional tillage treatments produced only 8.15 t/ha of grain, while tied ridges treatments produced 9.10 t/ha. According to Mairura *et al.* (2022), using linked ridges increases overall grain and stover production compared to using conventional tillage. Grain yield was lowest with conventional tillage methods, as opposed to tied ridges. Considering differences in soils and climate more studies are needed to determine whether or not linked ridges or regular tillage has a greater impact on crop yields. This would provide information that farmers can use to increase crop yield.

Green grams (*Vigna radiata*) also known as mung beans is an erect annual plant that grows to a height of 60 - 70 cm (Deiss *et al*. 2021). Mung beans perform best at altitudes between 50 – 1600 meters above sea level. Good output is ensured with an annual rainfall of as little as 650 mm, although the plant needs sufficient hydration from blooming through early and late pod fill. Late-season harvest losses and disease outbreaks are linked to high humidity and abundant rainfall (Ashworth *et al.,* 2020). When temperatures are low and moisture is plentiful, vegetation flourishes while pods are delayed or prevented from forming. Soils with a pH between 6.3 and 7.2 and a texture similar to sandy loam are ideal for growing mung beans. Asian countries including China, Thailand and India, are major producers of this crop. Green grams also do well when planted with other crops like maize and sorghum (Otieno *et al.*, 2021).

Research has shown that green grams do well under conventional tillage system as compared to tied ridge system due to its sensitivity to excess water. According to research done by Kurothe *et al.* (2014), in India's semiarid regions, the conventional tillage plots improved surface drainage, which helped green gram yields. The crop yield under conventional tillage was 42% higher than the tied ridge practice. This result was supported by Mugo *et al.* (2020), who found that conventional tillage resulted in a 13.6 percent higher grain production than reduced tillage. Green gram grown on flat seedbed had significantly higher grain yield of 0.4 t/ha than those under tied ridges of 0.2 t/ha (Githunguri *et al.* 2016). This suggests that green grams perform best under less disturbed flat seedbed and are probably affected negatively by an excessive supply of water and waterlogging thus will most likely perform optimally under well drained soils as opposed to tied ridges which are likely to engender stagnant water basins that are released gradually to the crop (Karukui *et al.* 2019).

2.2. Soil Fertility and Productivity in Kenya

Soil degradation, low levels of soil fertility, and low crop yields, are some of the key challenges that continue to face the agricultural sector in Kenya, more so in the semi-arid and arid regions (Mairura *et al.* 2022). By definition, soil fertility refers to the capability of the farming soil to support plant growth to maturity, and is often affected by elements such as the pH, texture, nutrient availability, and organic matter content (Nosheen *et al*. 2021). In Siakago, Embu County, poor or low soil fertility, accompanied by low rainfall and extreme weather conditions, has caused reduction in the agricultural yields. Soil degradation in the region has largely been facilitated by the region's tropical climate, which is majorly coupled with high temperatures and rainfall (Njau, 2017). The region also has clay-loam soil and is frequently affected by compaction and erosion which is as a result of the poor soil conservation practices, and which also in turn lead to the soil losing fertility as well as soil degradation. This means that the area would generally have a large number of its inhabitants living below poverty lines due to their dependence on farming which gives decreased crop yields.

Kenya in general, including Siakago, has continued to face low crop yields due to poor soil and crop management. Crop yields generally rely on soil fertility, climatic conditions, as well as pest and disease management (Wawire *et al*. 2021). For this reason, Siakago experiences low crop yields due to the low levels of soil fertility, inadequate irrigation, as well as the lack of proper crop management practices. As a result, it has led to low and declining agricultural productivity, increased poverty, and cumulatively food insecurity. It is also noted that soil degradation and low crop yields have had both economic and social consequences for farmers in the Siakago region. These ongoing low crop yields can lead into reduced income, increased poverty, and limited food security (Njau, 2017). Furthermore, soil degradation and low crop yields can contribute to environmental degradation, reduced biodiversity, and increased greenhouse gas emissions.

Sustainable agricultural practices are recommended in a bid to tackle the difficulties faced by farmers in Siakago. These practices are geared towards enhancing soil fertility and productivity. Conservation agriculture is one of the practices that can effectively help achieve sustainability, as it involves minimum tillage or no-till farming, developing soil cover crops, and rotating crops (Musafiri *et al.* 2023). Conservation agriculture can also assist in reducing soil erosion which in turn will facilitate improved soil fertility, and increased crop yields. In addition to conservation agriculture, other sustainable agricultural practices include mulching, contour farming, and terracing are essential. These methods help improve the crop yields by acting as agents of reducing soil erosion and improving soil fertility. Soil conservation practices will also help reduce soil degradation and improve on sustainable agricultural development practices.

Soil degradation and low crop yields pose significant challenges for farmers in the area, with significant economic and social consequences (Nayakekorale, 2020). To address these challenges, adopting sustainable agricultural practices that promote soil fertility and productivity is essential. Conservation agriculture, soil conservation practices, and crop diversification would come in handy for this function. By adopting these practices, farmers in Siakago can improve their agricultural productivity, reduce poverty, and promote sustainable agricultural development.

2.3 Soil Fertility Management

Soil fertility management is a crucial aspect of sustainable agriculture, particularly in semi-arid regions where soil fertility loss is a significant challenge. Semi-arid regions face unique challenges when it comes to managing soil fertility, mostly due to insufficient precipitation and financial constraints that prevent the purchase of necessary inputs, especially relatively costly inorganic fertilizers, which are typically imported (Sullivan *et al.* 2020). Soil fertility loss is typically exacerbated by nutrient withdrawals, which compounds the original problem. Nutrient loss happens when farmers don't replenish soil nutrients after harvest, when soil is eroded, or when they don't use soil nutrients wisely (Pole *et al.* 2018).

One of the most common soil fertility management methods is the use of organic amendments such as compost, manure, and green manure. These amendments can improve soil fertility by increasing the levels of nutrients such as nitrogen, phosphorus, and potassium in the soil (Shah *et al.* 2021). Organic amendments can also improve soil structure and increase the water-holding capacity of the soil (Baj *et al.* 2020). Another soil fertility management method is the use of inorganic fertilizers such as nitrogen, phosphorus, and potassium (NPK) fertilizers. These fertilizers can provide a quick fix for soil fertility problems, but they can also have negative environmental impacts if not used properly (Deiss *et al*. 2021). Inorganic fertilizers can also deplete the soil of its natural nutrients, leading to soil degradation (Pole *et al.* 2018).

Integrated soil fertility management (ISFM) is an approach that combines the use of organic and inorganic fertilizers with conservation agriculture practices, such as crop rotation, cover cropping, and reduced tillage (Ashworth *et al.* 2020). Integrated soil fertility management can improve soil fertility by increasing the levels of nutrients in the soil, improving soil structure, and reducing soil erosion (Weifeng *et al.* 2022). Lack of soil fertility, notably nitrogen and phosphorus shortages, poses substantial biophysical limits on farming in East and Southern Africa's semi-arid regions (Pole *et al*. 2018). Semiarid soils in Eastern and Southern Africa typically lack adequate levels of key soil nutrients such as nitrogen and phosphorus. Some of the soil properties considered during determination of soil fertility include soil pH, total nitrogen, organic carbon, and phosphorus (Morris & Mohiuddin, 2020). These soil attributes are affected by the interaction between soil fertility and micro-organisms. Usually, low soil pH; severely undermine the microbial activities resulting in the minimum rate of decomposition. A Soil fertility management relies on an improved knowledge of nutrient imbalances caused by changes in pH and the addition of new nutrients.

Application of the right proportions of fertilizer, both organic and inorganic, can boost soil fertility (Smith *et al.* 2016). However, it is paramount for farmers to be aware of the eventual outcomes of the application of each type of fertilizer (Weifeng *et al*. 2022). Organic fertilizer and manure have less adverse impacts on the soil in the long run (Mairura *et al.* 2022). Soil quality and structure influence how much organic and inorganic fertilizers can be used in semi-arid areas (Njiru *et al*. 2023). Natural components of soil increase while using organic fertilizer. In contrast, inorganic fertilizer use boosts mineral availability in the soil quickly (Nosheen *et al*. 2021).

Soil fertility management in semi-arid regions requires a holistic approach that considers the complex interactions between soil, climate, and agricultural practices. This approach should involve the use of organic and inorganic fertilizers, as well as conservation agriculture practices that promote soil conservation and reduce soil erosion. This approach is designed to improve soil fertility and promote sustainable agriculture while considering the long-term sustainability of soil fertility. It is important to take into account the intricate interactions between soil, climate, and agricultural practices when developing soil fertility management strategies.

2.3.1 Soil properties under organic and inorganic fertilizers

Organic fertilizer is any material that is part of or originated from living organisms. Examples of organic fertilizers include farmyard manure, green manure, chicken manure, urban waste. Soil supplements made of organic materials, like cow manure, chicken droppings, and farmyard manure, have been demonstrated to be effective in enhancing crop yields in a number of studies (Mugo *et al*. 2020). Farm manure can be useful in enriching the soil in place of inorganic fertilizer since it releases nutrients gradually over time and stimulates soil microbes (Karuku *et al.* 2019).

Since manure decomposes more slowly than artificial fertilizers, farmers must use more of it to meet crop nutrient needs; yet, this extra fertilizer has positive long-term consequences on future crop development and harvests (Weifeng *et al.* 2022). Other potential benefits include enhanced fertility and structure, increased soil organic matter building, soil pH buffering, and enhanced water retention capacity after manure application (Ashworth *et al.* 2020).

Farms in arid and semiarid regions typically have sandy soils with poor water retention that can benefit from organic matter additions. There is evidence that organic materials can improve soil structure and soil physical qualities when added to these soils because of its propensity to form water-soluble aggregates (Mwadalu, 2014). Increasing root penetration and water-holding capacity while decreasing compaction and erosion is the result of adding organic matter (Wawire *et al*. 2021). Increased crop yields is achieved because organic inputs enhance the soil's nutrients properties, such as water conservation and nutrient release (Mugo *et al.* 2020).

Fertilizers ensure that nutrients are available in the soil for plant uptake and thus being responsible for the production boost. Decomposition of FYM releases nutrients, which, according to research by Otieno *et al.* (2021), stimulate soil microbial activities and improve soil health. Soil nutrient availability can be improved using organic manure amendments. Manufactured with at least one necessary plant nutrient, inorganic fertilizers are used to promote plant development. They are highly concentrated forms of nutrients that plants can easily absorb. It is possible for excess nitrogen and phosphorus to be leached or discharge into groundwater if fertilizers are applied incorrectly and the crop does not take up the fertilizer. This lowers the usage efficiency of the fertilizer (Sun and Li, 2021).

Soil productivity can be maintained and increased through application of both natural and synthetic fertilizers (Gathungu *et al.* 2015). Soil fertility was raised by using mineral fertilizer with dung from livestock, and subsequent sorghum grain and stover yields were 3.94 t/ha and 8.01 t/ha, respectively (Kugedera *et al.* 2018). Manures and fertilizers enhance a crop's water efficiency (Kathuli & Itabari, 2015). Wawire *et al.* (2021) and Mugo *et al.* (2020) describe similar findings, stating that Mbeere farms need annual nutrient replenishment from manures, fertilizers, and the return of crop leftovers. This is because the soils are naturally not very fertile and the high temperatures hasten the decomposition of organic substances. Because of this, more studies into organic and fertilizer use is required in Mbeere, Kenya.

Kathuli and Itabari (2015) found that adding fertilizer to tied ridging considerably boosted sorghum grain output by 3-5%. Similar findings were made by Njeru *et al.* (2015), who discovered that 3.7 t/ha of sorghum could be produced along with connected ridges with only a half-dose application of manure and nitrogen. Nutrients like phosphorus, potassium, calcium and magnesium tend to decrease with soil depth, providing evidence of their transport from the surface to the subsoil (Morris & Mohiuddin, 2020). Nutrients are lost from the root zone through leaching and mass flow. Leaching occurs when a solute dissolve in water through soil matrix to the lower part. Mass flow, on the other hand, takes place in events where solute and water surround the soil matrix and go down the profile via porous openings like macropores, wormholes, mole holes, cracks, and root channels. Leaching results in loss of applied nitrogenous fertilizers and mineral nitrogen in the soil systems (Sullivan *et al.* 2020). The right tillage method can reduce these losses (Baj *et al*. 2020). This research analyzes the outcomes of different agricultural systems, tillage methods, and organic and inorganic inputs in Siakago, Embu County.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Site

The study took place at the Agricultural Technology Development Centre (ATDC), Siakago in Mbeere North sub-County, Embu County (0°34'23.9"S 37°38'18.2"E). The Centre falls under agro-climatic zones IV-2 (Kisaka *et al.*, 2011) which is semiarid with average agricultural potential. The yearly precipitation averages between 200 to 300 mm, average annual evaporation of 1550 to 2200 mm and mean annual temperatures of 22-24^{0}C. Mbeere experiences bimodal rainfall pattern, with the shorter and less consistent one lasting between the months of March and May, and the long rains coming between the months of October and January, which is more consistent. The first season experiences about 40% of annual moisture while the second experiences about 60%. Extreme rainfall frequently surpasses the soil's ability for infiltration, leading to crusting, runoff, and erosion. The site has diverse soil types, made of Rhodic Ferralsols and Haplic Lixisols. The Rhodic Ferralsols (the main soil type at the site) has good drainage, a rich red color, and a friable clay content (Ngetich *et al*. 2014).

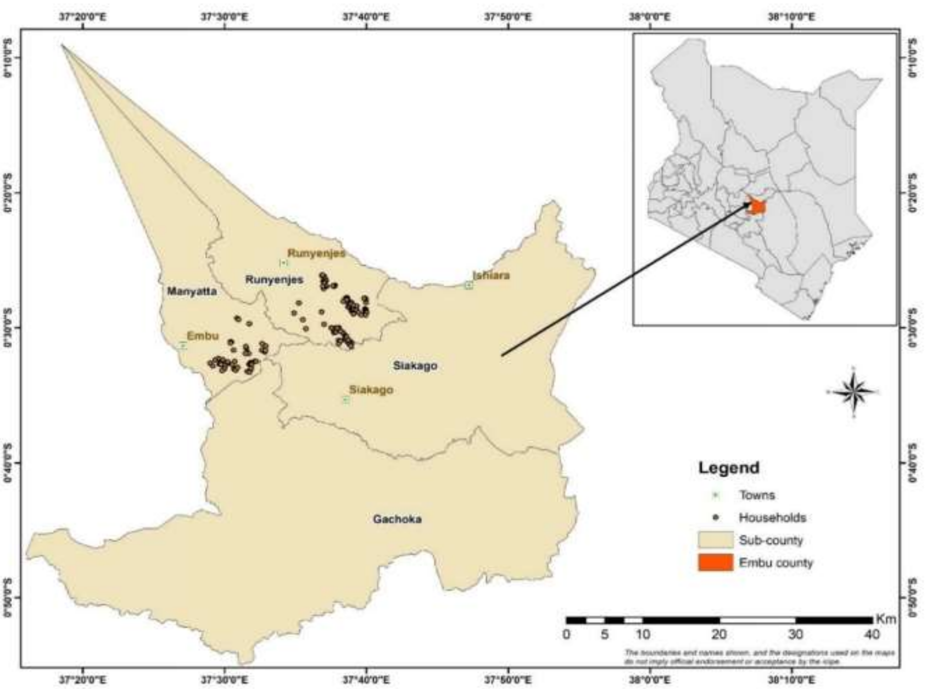

Figure 3.1: Map of study area (Source: Wangithi et al., 2021)

3.2 Experimental Design and Treatments

The effectiveness of 24 treatments was evaluated employing a split-split plot design arranged in randomized complete block design (RCBD) Both conventional and tied ridge tillage were used as part of the treatments. Three cropping systems (green grams, sorghum and green grams and sorghum intercrops) and four soil fertility input regimes ([no inputs], [60 kg DAP ha^{-1}], fully decomposed farmyard manure (5.0 t ha^{-1} manure), and the use of two distinct doses of fertilizer (2.5 t ha^{-1} of manure and 30 kg DAP ha^{-1} of chemical fertilizer) (Njiru *et al.*, 2023) (Table 3.1) were used. The primary plots were assigned to the tillage methods, while the secondary and tertiary plots were designated for the cropping systems and fertility input (types), respectively. Three replicates were conducted using a sub plot size of 6x4 m. At the time of sowing, either in the planting holes or on the knotted ridges, organic or organic fertilizers were applied. The plot covered 0.5 ha of land and was fairly level.

Table 3.1: Treatments combination for the effect of tillage practices, cropping systems and fertility input trials in Siakago, Embu County.

No.	Tillage	Cropping system	Fertilizers
1	Conventional tillage	Sole sorghum	Nil= No inputs
2	Conventional tillage	Sole sorghum	FF= 60 kg DAP ha^{-1}
3	Conventional tillage	Sole sorghum	FM = 5.0 t ha^{-1} manure
4	Conventional tillage	Sole sorghum	HMF= 2.5 t ha^{-1} + 30 kg DAP ha^{-1}
5	Conventional tillage	Grams	Nil= No inputs
6	Conventional tillage	Grams	FF= 60 kg DAP ha^{-1}
7	Conventional tillage	Grams	FM = 5.0 t ha^{-1} manure
8	Conventional tillage	Grams	HMF= 2.5 t ha^{-1} + 30 kg DAP ha^{-1}
9	Conventional tillage	Sorghum+Grams	Nil= No inputs
10	Conventional tillage	Sorghum+Grams	FF= 60 kg DAP ha^{-1}
11	Conventional tillage	Sorghum+Grams	FM = 5.0 t ha^{-1} manure
12	Conventional tillage	Sorghum+Grams	HMF= 2.5 t ha^{-1} + 30 kg DAP ha^{-1}
13	Tied ridges	Sole sorghum	Nil= No inputs
14	Tied ridges	Sole sorghum	FF= 60 kg DAP ha^{-1}
15	Tied ridges	Sole sorghum	FM = 5.0 t ha^{-1} manure
16	Tied ridges	Sole sorghum	HMF= 2.5 t ha^{-1} + 30 kg DAP ha^{-1}
17	Tied ridges	Grams	Nil= No inputs
18	Tied ridges	Grams	FF= 60 kg DAP ha^{-1}
19	Tied ridges	Grams	FM = 5.0 t ha^{-1} manure
20	Tied ridges	Grams	HMF= 2.5 t ha^{-1} + 30 kg DAP ha^{-1}
21	Tied ridges	Sorghum+Grams	Nil= No inputs
22	Tied ridges	Sorghum+Grams	FF= 60 kg DAP ha^{-1}
23	Tied ridges	Sorghum+Grams	FM = 5.0 t ha^{-1} manure
24	Tied ridges	Sorghum+Grams	HMF= 2.5 t ha^{-1} + 30 kg DAP ha^{-1}

Note: Fertility inputs: HMHF = Half manure Half Fertilizer; FF = Full fertilizer; FM = Full manure; Nil = No fertilizer or manure input; gram = green grams; sorghum + grams = intercrop

3.3 Field Experiment

3.3.1 Land preparation

Land was cleared by removing the previously growing pigeon peas using pangas and jembes followed by cultivation using the conventional or tied ridges during the dry season. *Conventional tillage* involved land tilling and harrowing using hand hoes. This was done during the dry season to avoid soil compaction. *Tied ridges:* Approximately 15 cm deep furrows with their associated ridges were made at 75 cm apart one week before seeding date.

3.3.2 Crops sowing

Planting was performed at the onset of the rains in mid- March during the long rains and mid- October during the short rains. Sorghum variety tested was Serena and Green gram variety tested was N 26 from East African Seed Company. *Sole-sorghum:* Irrespective of the tillage system, planting distances for the sorghum were 75 cm (inter-row) and 25 cm(intra-row) spacing. Two seeds per hole were maintained. The crop was planted on the furrows in case of the tied-ridge tillage system.

Sole-green grams: Irrespective of the tillage method, green grams were spaced at 60 cm (inter-row) by 15 cm (intra-row) spacing. *Sorghum + green gram intercrop:* For sorghum-green gram intercropping system, one row of green gram was planted between two sorghum rows at 45 cm and 15 cm spacing along the row.

3.3.3 Fertilizer and manure application

Di-Ammonium Phosphate (DAP) fertilizer was used to supply N and P at planting as per the experimental treatment at a rate of 60 kg DAP ha^{-1} . In these experiments, DAP was applied at the rate of 60 kg DAP $ha^{-1}$for the full fertilizer treatment and at 30 kg DAP ha^{-1} for the treatment with only half mineral fertilizer rate. Application of the DAP fertilizer was done at planting time by measuring the quantity and mixing it thoroughly with the soil prior to planting (Ameen *et al*. 2017).

The organic manure used was farm yard manure sourced from neighboring farmers at the ATDC, Siakago when fully decomposed. Manure was broadcasted on plots and incorporated into the soil using a hoe before planting. The handful of fully decomposed organic manure application was done due to the earlier calibration that was done which indicated that the handful amount delivered the desired rate of 5.0 t ha^{-1} (Liu *et al.*, 2022).

3.4 Field Management Practices

3.4.1 Weeding

Weeds were uprooted after every two weeks in order to enhance proper growth of the crops by avoiding competition for sunlight, moisture and nutrients.

3.4.2 Pest and disease control

The trial was monitored regularly to control insect pests, diseases and other probable sources of variation. Stalk borers, aphids and other insects were controlled by spraying insecticide KUNG FU 5 EC (50 g/L Lambda-cyhalothrin) by mixing 20 ml of insecticide in 15 L Knap sack sprayer (Mahmoud *et al.,* 2024). Casual guards were engaged at sorghum milk, hardening and physiological maturity stage to scare bird pests.

3.4.3 Harvesting of sorghum and green gram

Grain sorghum was considered to be mature once the head had fully formed and moisture content dropped. The crop was harvested by cutting the head using a panga. Green grams matured within 60 - 90 days after sowing. Harvesting was done when the pods had turned black. Harvesting involved picking the dry pods from the plant.

3. 5 Data collection

3.5.1 Soil data

Soil was sampled initially within the experimental field using the zigzag method in ten points per block to make a composite sample at a depth of between 0 - 20 cm using an auger. The samples were then transferred to pre labeled containers. The procedure was repeated to the remaining points then mixed together to form a composite sample (Akyar, 2012). Three days prior to planting, the initial soil fertility level was evaluated by randomly collecting composite soil samples. At the time of harvest, composite soil samples were taken at random from each plot in order to analyze any changes in the chemical features of the soil that may have been caused by the different treatments. The gravimetric approach was used to calculate the bulk density.

3.5.2 Soil preparation and analysis

The soil samples from the field were taken to The National Agricultural Research Laboratories (NARL) at Kabete for analysis. The soil was ground and sieved using a

2 mm holed sieve post oven drying at 40 degrees Celsius, before evaluating its composition (Dutra, J.C., & Batitucci, 2024). The pH, Total soil Nitrogen (TSN), Total Organic Carbon (TOC), available soil Phosphorus, Potassium, Magnesium, Manganese, Zinc and Copper levels were determined following the methodologies outlined by Dutra, J.C., & Batitucci, 2024.

The Mehlich double acid technique by Dutra, J.C., & Batitucci, 2024 was employed to extract P, K, Ca, Mg, and Mn by combining 0.1 N HCl and 0.025 N H_2SO_4 at a 1:5 soil: volume ratio (w/v). Calcium and Potassium levels were quantified using a flame photometer, while Magnesium and Manganese were measured with a calorimeter as per Dutra, J.C., & Batitucci, 2024. To analyze Total Organic Carbon (TOC), calorimetric assessment involved heating a soil sample to 150 degrees Celsius for 30 minutes in acidified dichromate to ensure complete oxidation of organic C. Subsequently, the digest was treated with barium chloride, left overnight, and then subjected to spectrophotometric analysis to determine C content.

The macro-Kjeldahl digestion method (Dutra, J.C., & Batitucci, 2024) was utilized to determine the total nitrogen content. In this process, total nitrogen present in various organic materials was transformed into ammonium using sulfuric acid (H_2SO_4), potassium sulfate (K_2SO_4), and copper sulfate ($CuSO_4$) as catalysts. The pH of the soil-water mixture at a 1:1 ratio was measured using a pH meter to ascertain its acidity or alkalinity. Atomic absorption spectrometry (AAS) was utilized to establish the concentrations of Iron, Zinc, and Copper extracted from the soil using 0.1M Hydrochloric acid at a 1:10 ratio.

An atomic absorption spectrometry (AAS) was utilized to determine the concentrations of the three minerals elements namely Iron, Zinc and Copper that were extracted from the soil using 0.1M Hydrochloric acid with a ratio of 1:10. The hydrometer test was used to analyze soil structure (no chemical pre-treatment to remove organic matter and other cementing agents) (Dutra, J.C., & Batitucci, 2024).

3.5.3 Rainfall and chlorophyll content

A manual rain gauge was used to record the site's daily precipitation. To conduct a physiological evaluation of leaf chlorophyll content, we employed Soil Plant Analysis Development (SPAD) - 502 plus to measure its intensity and concentration. The

SPAD readings for each plot were taken at the flowering stage on the leaves of six randomly selected plants per plot. On each plant, measurements were obtained at the centre of the leaf between the leaf tip and leaf base and in between leaf midrib and the edge of the blade. An average value for each plot was automatically calculated by the machine and recorded (Jargal *et al*., 2021).

3.5.4 Days to 50 % flowering and plant height

Days to 50 % flowering: Recorded in days after planting and coincided with the initial developmental stage (the first flower opens) when 50% of the plants had one or more open flowers. Plant height at sprouting. This was achieved by measuring the whole plant from the ground level to the last leaf using a tape measure. (8 random sorghum and green gram plants per plot)

3.5.5 Grain and biomass yield

Biomass was obtained at harvest by uprooting the whole plant and weighing all plants in a $24m^2$ net plot. Sorghum heads were harvested at maturity, put in a shed and dried by spreading on a bag for one week. Later, it was threshed and the grains weighed per net plot and the total weight used to calculate the seed yield per hectare in Mg ha^{-1}. The total weight was used to calculate the seed yield per hectare in (Mg ha^{-1}).

3.5.6 Harvest index

This is the ratio of the amount of grain that was dried to the amount of biomass that was dried above ground. Harvest Index was determined using Equation 1.

$$Harvest\ Index\ (HI) = \frac{Grain\ Yield}{Aboveground\ dry\ biomass}$$ ………………… *Equation 1.*

3.5.7 Land equivalent ratio (LER)

This is the sole cropped area needed to produce equal yield as that under inter cropping at the same management level. It is the ratio of inter cropped yields to the sole-crop yields (Equation 2).

$$LER = \frac{Yield\ of\ Sorghum\ Intercrop}{Yield\ of\ Sole\ Sorghum}$$ …………………..……………………… *Equation 2*

3.6 Data Analysis

Prior to data analysis, the data was entered into an Excel worksheet, cleaned, and any outliers were verified using boxplots. In order to investigate trends, other descriptive tests were also run. Using Genstat software, an ANOVA was performed to examine the main effects of various treatments as well as the interactions between cropping type, tillage, and soil fertility management in a Split-Split-Plot design. The Turkey LSD (0.05) technique was used to separate the means. Moreover, PCA techniques were applied on the data using R software to look for patterns in the relationships between various soil fertility metrics.

CHAPTER FOUR

RESULTS

4.1 Rainfall

The results for cumulative rainfall for the four planting seasons are presented in Figure 4.1. It is noted that each sites cropping season rainfall distribution and total amount were different. The long rains started in March or April while the short rains generally started in October. The cropping seasons ended in September and February/March, respectively. These seasons are hence designated as Long Rains (LR) and Short Rains (SR).

The SR 2018 cropping season was characterized by medium amount of rainfall between October and December of 2018 and had 36 days of rainfall. During this season, the months of January and February 2019 remained relatively dry. In the LR 2019 season, While April and May saw a fair amount of precipitation, June and July saw almost none. There was a total of 30 days of damp soil conditions for the full LR 2019 cropping season, which lasted from April 23rd to June 10th. Rains began on October 1st (the start of the SR 2019 cropping season) and didn't let up until February 26th, 2020. This indicates that there were roughly 85 days of saturated soil this season. The SR 2020 cropping season experienced high rainfall amounts in November whereas December to February had minimal rain. Cumulatively, during the trial periods, 380 mm during SR 2018, 905 mm during LR 2019, 1383 mm during SR 2019- and 696-mm during SR 2020 rainfall was received.

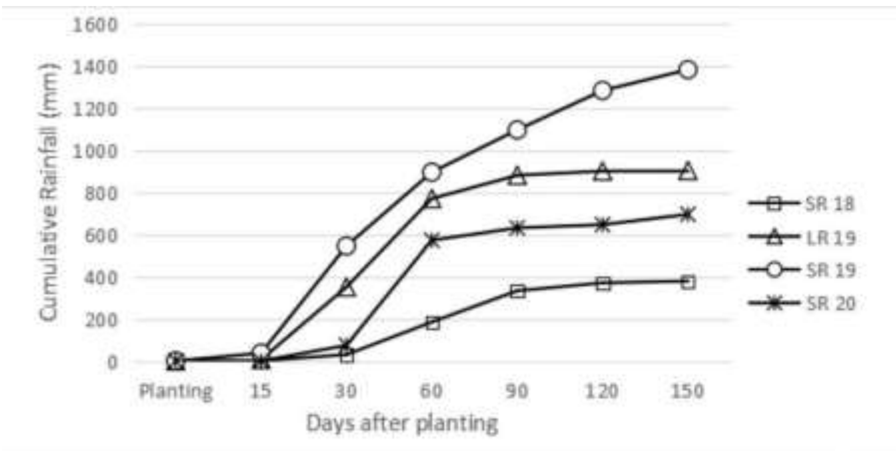

Figure 4.1: Cumulative Rainfall at Siakago, Embu, Kenya during the four study seasons (September 2018 to February 2021)

4.2 Soil Chemical composition

The original chemical properties of the soil at the investigation location are detailed in Table 4.1. The soil had a low carbon content and was acidic. It was also lacking in calcium, magnesium, copper, and zinc.

Table 4.1: Initial chemical characteristics of the soil at the study site.

Soil pH	Total N %	Total C %	P ppm	K me%	Ca me%	Mg me%	Mn me%	Cu ppm	Fe ppm	Zn ppm
5.81	0.1	0.73	10	0.68	2.4	1.22	0.58	1.75	24.6	1.68

4.3 Quality of the Farmyard Manure

Table 4.2 displays the chemical constituents found in the farmyard manure (FYM) that was used in the experiment.

Table 4.2: Chemical composition of farmyard manure

Soil pH	Total N %	Total C %	P ppm	K me%	Ca me%	Mg me%	Mn me%	Cu ppm	Fe ppm	Zn ppm
5.7	1.12	1.19	7.21	0.08	5.04	2.08	0.66	5.22	15.48	4.66

Table 4.3: Critical nutrient rating levels used to guide fertilizer recommendations.

Determined Parameter	Low	Adequate/ favourable	Rich or Toxic
pH	<5.0	5.5-8.0	<5.0 ->8.0
Organic Carbon (OC %)	<2.7	≥2.7	
Nitrogen (N %)	<0.2	≥2.0	
Phosphorus (P ppm) (Mehlic method)	<30	30-80	
Phosphorus (P ppm) (Olsen method) *	0-10	11-15	>15
Potassium (K me 100g)	<0.24	0.24-1.5	1.5+
Zinc (Zn ppm)	<5.0	≥5.0	

Table 4.4: Soil properties after application of different tillage systems, cropping systems and soil fertility inputs and their interaction.

Factor	MEAN SOIL PARAMETER VALUE										
Tillage Practices (T)	**pH**	**OC %**	**N %**	**P ppm**	**K me/100g**	**Ca me/100g**	**Mg me/100g**	**Fe ppm**	**Cu ppm**	**Mn me/100g**	**Zn me/100g**
Tied ridge (TR)	5.42[a]	0.47[a]	0.04[a]	7.99[a]	0.41[a]	4.90[a]	1.31[b]	37.36[b]	5.39[a]	0.75[a]	5.18[a]
Conventional tillage (CT)	5.38[a]	0.36[a]	0.04[a]	6.35[b]	0.37[a]	5.34[a]	1.71[a]	49.59[a]	4.29[b]	0.71[a]	5.18[a]
P value	0.5009	0.7448	0.48	0.0003 ***	0.3696	0.1575	0.0312 *	0.0067**	0.00227 **	0.7395	1
Cropping Systems(C)											
Sole sorghum cropping system	5.35[a]	0.37[a]	0.03[a]	6.91[a]	0.36[a]	4.82[a]	1.67[a]	44.83[a]	4.78[a]	0.72[a]	5.18[a]
Sole Green grams cropping system	5.50[a]	0.50[a]	0.05[a]	7.56[a]	0.41[a]	5.14[a]	1.69[a]	44.88[a]	4.65[a]	0.64[a]	5.18[a]
Intercrop cropping system	5.35[a]	0.37[a]	0.04[a]	7.03[a]	0.39[a]	5.41[a]	1.17[b]	40.73[a]	5.09[a]	0.83[a]	5.18[a]
P value	0.849	0.219	0.8241	0.8537	0.5843	0.4874	0.0413*	0.9552	0.8888	0.4524	0.2732
Fertility											
Full fertilizer at 60 kg DAP ha-^{1} (FF)	5.40[a]	0.34[a]	0.03[a]	7.52[a]	0.35[a]	5.29[a]	1.73[a]	45.02[a]	4.93[a]	0.61[a]	5.37[a]
Full FYM at 5.0 t ha^{-1} (FM)	5.39[a]	0.57[a]	0.05[a]	7.05[a]	0.37[a]	4.93[a]	1.60[a]	42.32[a]	4.59[a]	0.75[a]	5.22[a]
Half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha-^{1} (HMHF)	5.44[a]	0.58[a]	0.04[a]	7.12[a]	0.43[a]	5.43[a]	1.36[b]	45.66[a]	4.95[a]	0.83[a]	5.25[a]
Unamended check (control)(NIL)	5.37[a]	0.38[a]	0.04[a]	6.97[a]	0.39[a]	4.84[a]	1.36[b]	40.91[a]	4.89[a]	0.73[a]	4.88[a]
P value	0.0736 .	0.1458	0.0689.	0.4952	0.6344	0.2949	0.0319 *	0.8485	0.6053	0.294	1
Significance Levels											
Fertilizer X Tillage	0.8274	0.5576	0.8787	0.7338	0.9476	0.3299	0.9835	0.9766	0.9625	0.8586	0.5002
Fertilizer X Cropping system	0.4978	0.0525	0.0014 **	0.9991	0.8232	0.2871	0.9125	0.9918	0.9945	0.7555	0.398
Fertilizer X Cropping system X Tillage	0.7941	0.3173	0.8502	0.5725	0.8428	0.807	0.99473	0.9958	0.9794	0.6989	0.6261

4.4 Effect of Treatments on Selected Soil Parameters

4.4.1 Soil pH

The results show that the soil was acidic. Tied ridge had a higher pH of 5.42 compared to conventional tillage with a pH of 5.38. Green grams planted as monocrops recorded the highest soil pH with a mean of 5.50 compared to sole sorghum and intercrop between sorghum and green gram. In the different fertility inputs, plots with half manure and half fertilizer (HMHF) recorded the greatest mean score of 5.44, while the plots that had not been altered (NIL) earned the lowest mean score of 5.37. Following the completion of the experiment over the course of three years and four seasons, the results of the soil analysis revealed that pH had an impact on the various treatments (Table 4.4).

4.4.2 Total organic carbon (OC)

Results (Table 4.4) indicates that the two tillage practices had no significant difference however the tied ridge (TR) had a higher mean of 0.47% compared to conventional tillage with a mean of 0.36%. The highest mean soil carbon concentration under conservation tillage was recorded in the intercropped plots, followed by green gram and sorghum, (Fig 4.2) while in Soil fertility management treatments significantly influenced soil carbon concentrations, with the lowest mean value recorded in the control plots (0.2 %), followed by fertilizer (0.35 %), half-fertilizer and half-manure (0.41) and the full manure treatment (0.61) (Fig 4.2). However, there was significant ($p \leq 0.05$) interaction between tillage and cropping systems. Both the cropping systems and the fertility inputs failed to show any statistically $p \leq 0.05$ significant differences. After three years and four seasons of trial, the findings of the soil analysis revealed that organic carbon had a beneficial impact on the outcomes of the various treatments (Table 4.4).

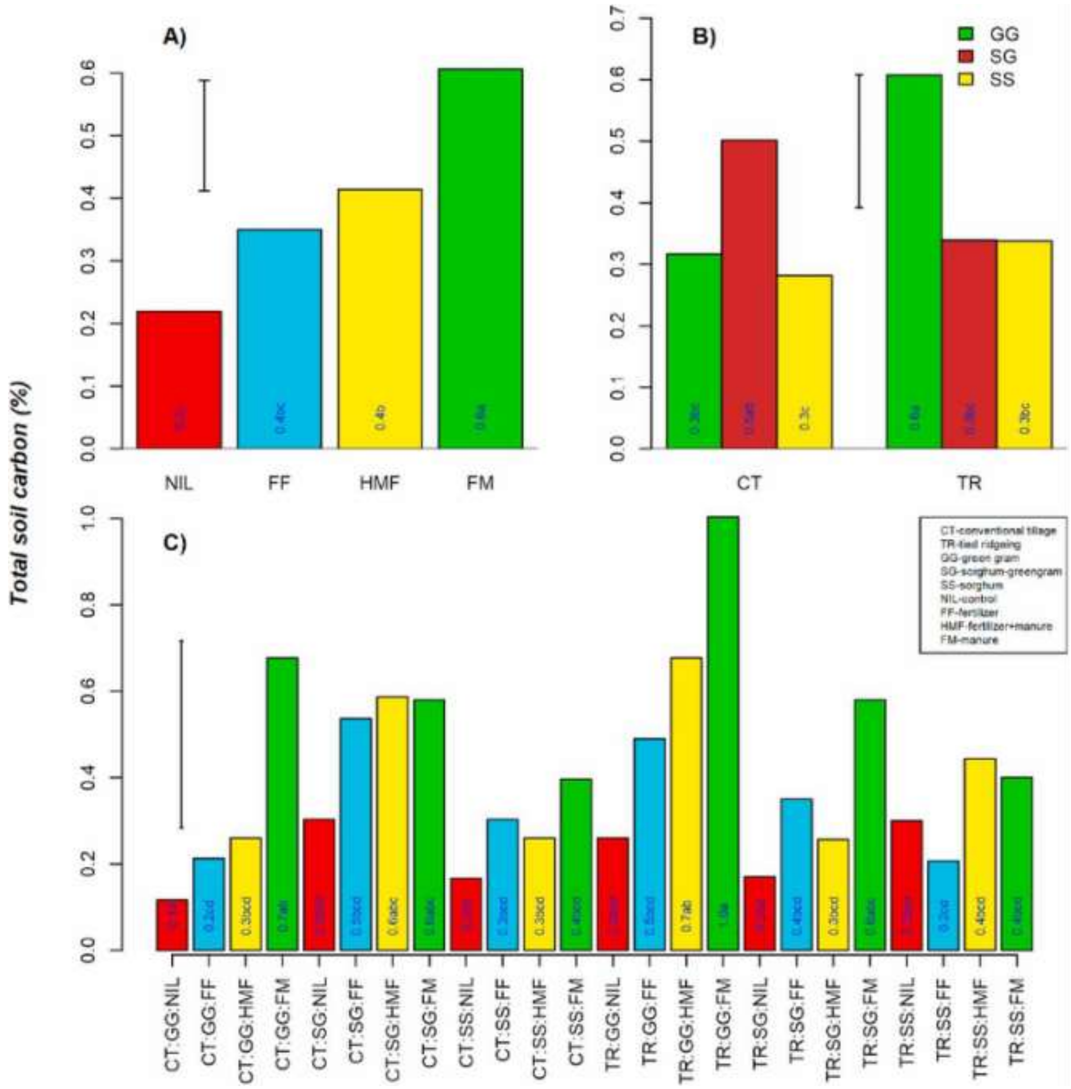

Figure 4.2: Soil tillage, crop system, and fertility management effects on soil carbon. Means followed by the same letters are not significant. Least significant differences are presented as error bars (A,-LSD-soil fertility management, B-Tillage*Cropping, C-Tillage*crop*soil fertility management).

4.4.3 Total nitrogen (N)

Total N content of the soils was similar among the two tillage practices. Regarding the cropping system (Fig. 4.3B), the total soil N was highest in the sole green gram (0.05 %), and similar for the intercrop and sole sorghum (0.03 %). Soil quantities taken from different fertility plots gave almost similar quantities of N though higher with a mean of 0.05% in plots that were applied with Farmyard Manure than in plots applied with Full Fertilizer (0.03) %, Half Manure Half Fertilizer (0.04) % and in plots without any amendments. (Table 4.4) Interaction between fertility inputs and cropping systems had significant ($p \leq 0.05$) difference. Also, the interaction of tied-ridging and green gram cropping gave the highest total soil N (0.06 %) (Fig. 4.3C), while the tied-ridging treatment with manure applications resulted in the highest total soil-N concentrations.

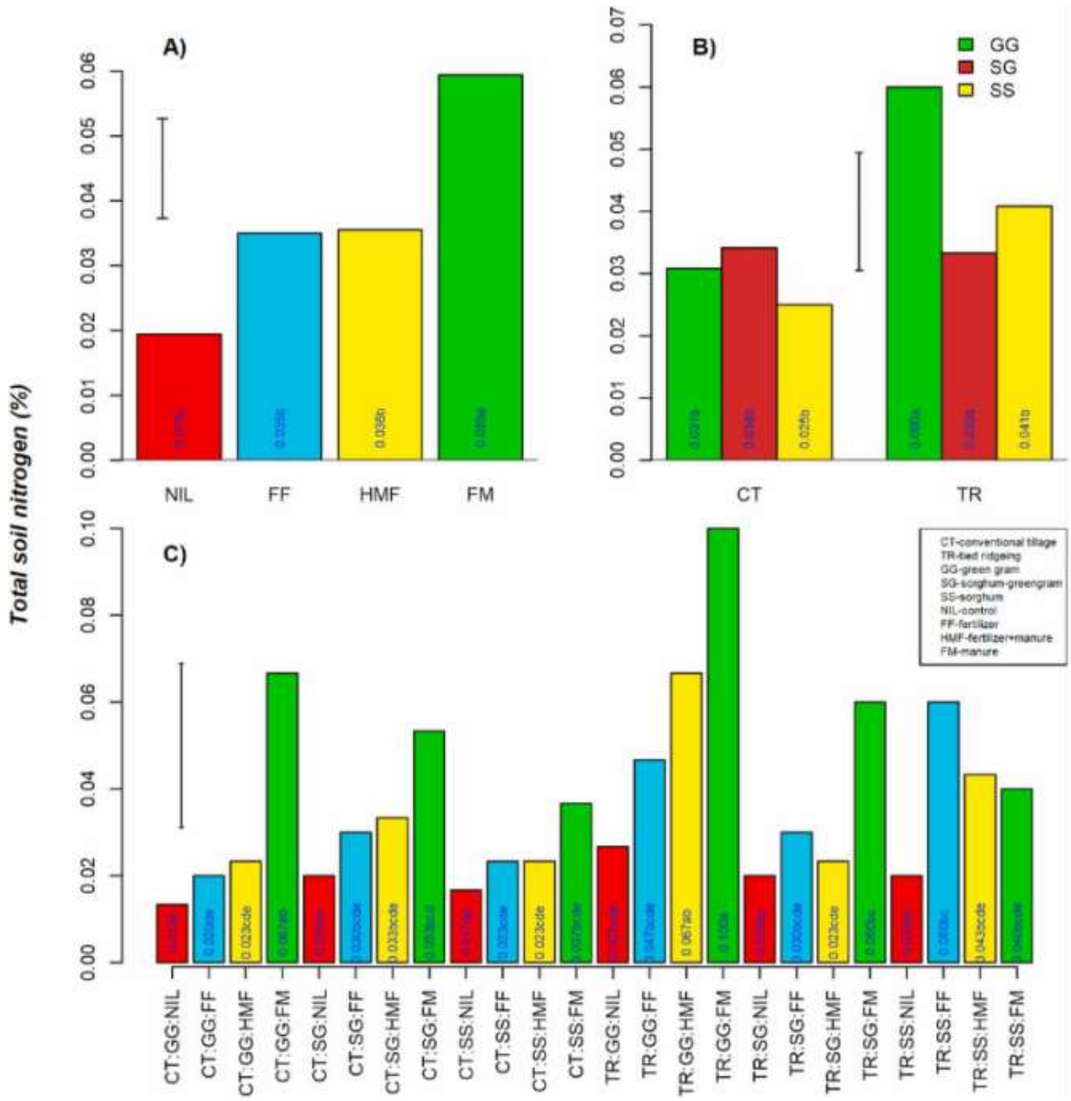

Figure 4.3: Soil tillage, crop system, and fertility management effects on total soil N. Least significant differences are presented as error bars (A,-LSD-soil fertility management, B-Tillage*Cropping interaction, C-Tillage*crop*soil fertility management interaction)

4.4.4 Extractable phosphorus (P)

There was a statistically significant ($p \leq 0.05$) difference on the level of exchangeable phosphorus (Table 4.4) which was higher under TR plots with a mean of 7.99 ppm than in CT plots with a mean of 6.35 ppm (Table 4.4). Regarding the crop system, the total soil P was highest in the sorghum (7.27 ppm), and was lowest in the green gram cropping system (6.74 ppm) (Fig. 4.4B). Soil fertility management treatments significantly influenced the extractable soil P distribution (Fig. 4.4 A–E) ($p = 0.015$). The manure treatment recorded the highest extractable soil P (7.75), followed by manure + fertilizer (7.29 ppm), fertilizer (7.13 ppm) and the control (5.94 ppm) (Fig. 4.4B). In relation to the cropping system, sorghum intercropping under tied ridges recorded the highest extractable soil P (7.44 ppm) while this was least in the green gram under conventional tillage (6.39). In all treatments, the crops under conventional tillage recorded the lower extractable soil P, compared to the plots under tied-ridging system (Fig. 4.4B). An evaluation of the soils at the start in 2018 and at the end of the trials in 2021 showed that different practices had a beneficial impact on the outcomes of the various treatments (Table 4.4).

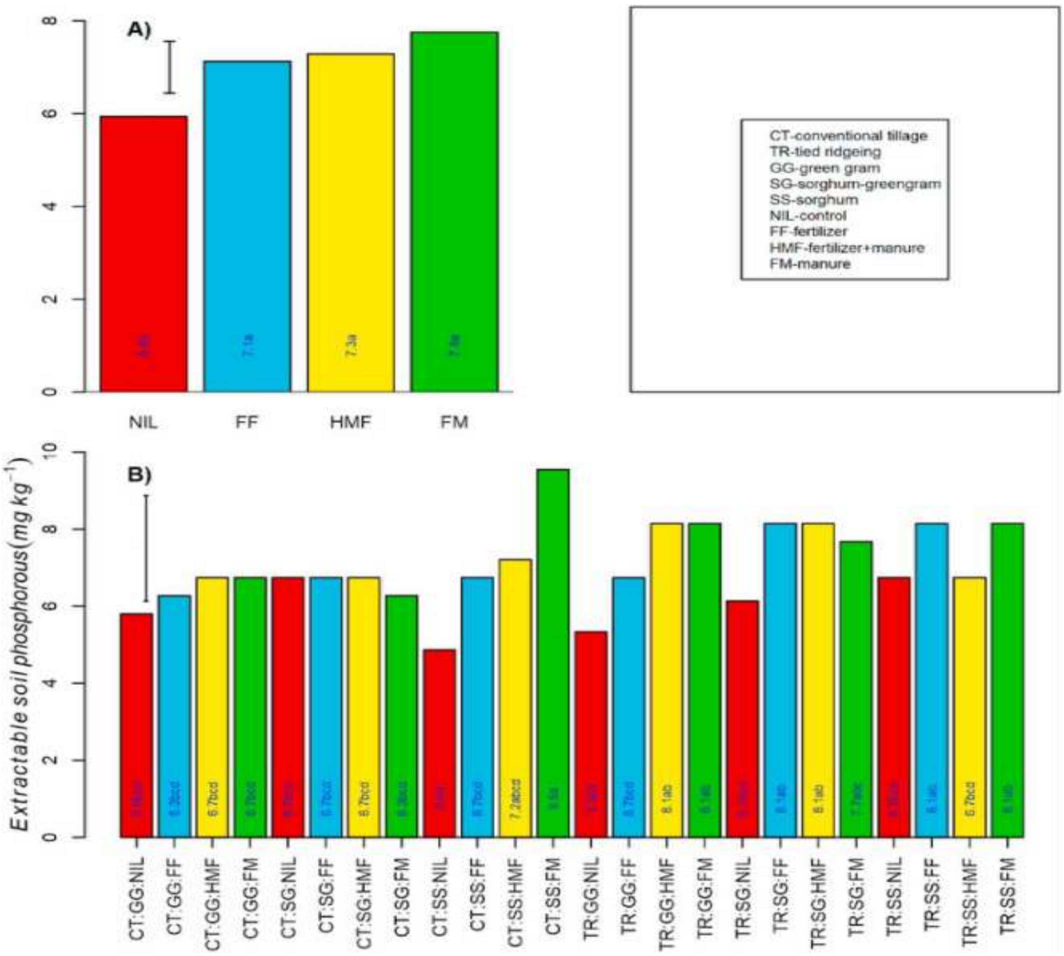

Figure 4.4: Soil tillage, crop system, and fertility management effects on soil P. Means followed by the same letters are not significant. Least significant differences are presented as error bars (A-LSD-soil fertility management, B-Tillage*crop*soil fertility management interaction).

4.4.5 Potassium (K+)

There was not a statistically significant ($p > 0.05$) difference, according to the results of an analysis of variance performed on the potassium data obtained from soil samples. (Table 4.4). However, it was higher under TR (0.41) me/100g than CT (0.37) me/100g, higher under sole green gram plots (0.41) me/100g than the other cropping systems and higher in HMHF (0.43) me/100g than in the FF, FM and NIL plots (Table 4.4).

4.4.6 Exchangeable bases (Ca++)

Table 4.4 demonstrates Ca was higher in CT (5.34) me/100g than in TR (4.90) me/100g. Intercrop between sorghum and green gram had a higher mean of 5.41 me/100g than the other two cropping systems. There were significant ($p \leq 0.05$) main effects attributed to soil fertility management for extractable soil Calcium (Fig. 4.5). The average soil extractable calcium was highest in the manure + fertilizer treatment (5.3). This was followed by fertilizer (4.95), manure (4.59), while the control recorded the least extractable calcium values. There were significant ($p \leq 0.05$) differences between all soil fertility treatments for extractable soil Ca. Regarding crop system, sorghum-green gram intercrops recorded the highest extractable soil Ca value (4.97), followed by sorghum (4.74) and green gram (4.52). In addition, the manure + fertilizer conventional tillage system recorded the highest extracted soil Ca value (5.70), while this was least in the tied-ridging without inputs (4.00).

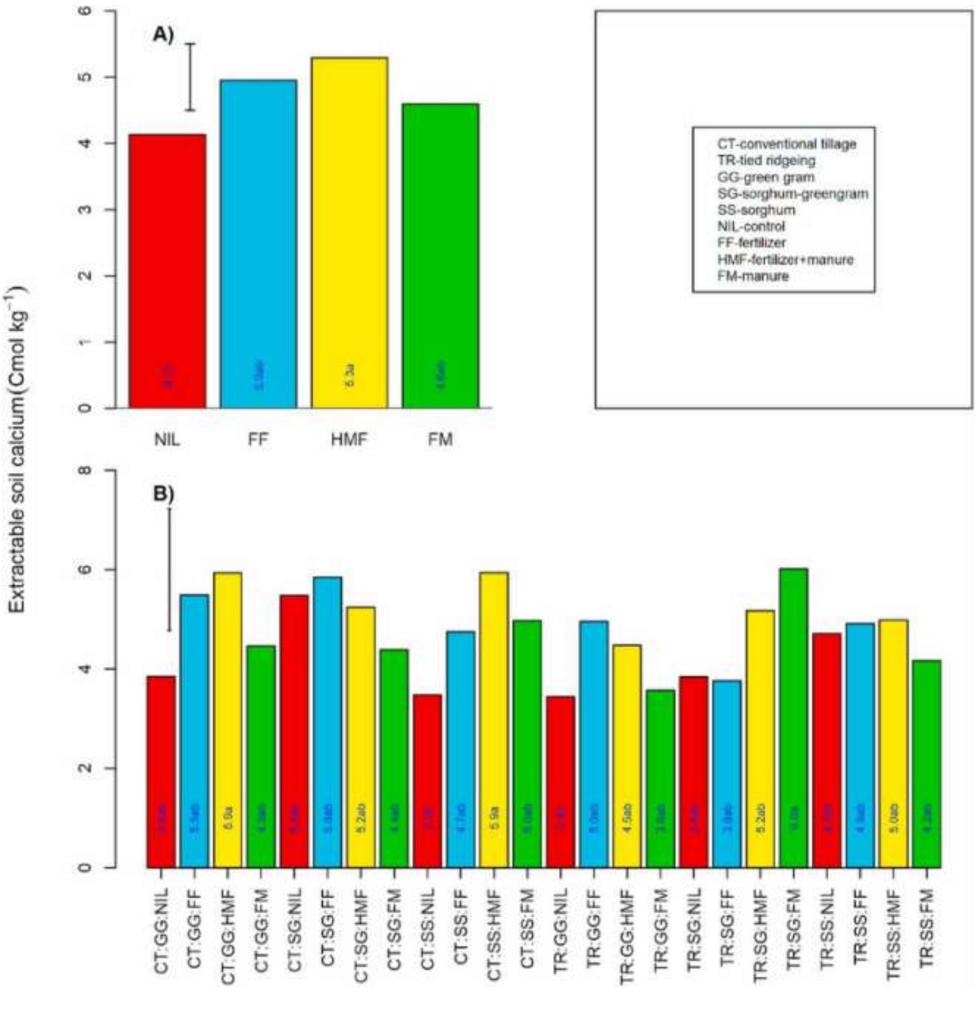

Figure 4.5: Soil tillage, crop system, and fertility management effects on soil Ca. Means followed by the same letters are not significant. Least significant differences are presented as error bars (A,-LSD-soil fertility management, B-Tillage*crop*soil fertility management interaction).

4.4.7 Exchangeable bases (Mg++)

The Magnesium content in the soil had a significant ($p \leq 0.05$) difference on the various factors considered with tillage practice recording a higher mean of 1.71 me/100g under conventional tillage and 1.31 me/100g under tied ridge plots. Sole green grams recording a higher mean of 1.69 me/100g than the sole sorghum and intercrop. There was a statistically significant ($p \leq 0.05$) difference between the fertility inputs, with FF recording the greatest mean of 1.73 me/100g and control plots showing the lowest mean of 1.36 me/100g. There was not a discernible difference that could be attributed to any of the several treatments (Table 4.4).

4.4.8 Iron (Fe)

Iron levels in the soil had a significant ($p \leq 0.05$) difference among the tillage practices. The conventional tillage recorded a higher mean of 49 ppm while the tied ridge had a lower mean of 37.36 ppm. Sole green grams had the highest mean of 44.88 ppm while the intercrop recorded the lowest mean of 40.73 ppm. HMHF had the highest mean of 45.66 ppm while the plots with no amendments had the lowest mean of 40.91 ppm. There was no statistical significance ($p > 0.05$) of the interactions (Table 4.4).

4.4.9 Copper (Cu)

The amount of copper in the soil had a significant ($p \leq 0.05$) difference among the tillage practices. The tied ridge tillage recorded a higher mean of 5.39 ppm while the conventional tillage had a lower mean of 4.29 ppm. Intercrop between sorghum and green gram had the highest mean of 5.09 ppm while the sole green gram recorded the lowest mean of 4.65 ppm. HMHF had the highest mean of 4.95 ppm while the plots with farmyard manure had the lowest mean of 4.59 ppm. The interactions had no significant ($p > 0.05$) difference (Table 4.4).

4.4.10 Manganese (Mn)

The level of Manganese in the soil had no significant ($p > 0.05$) difference among the tillage practices, cropping systems and fertility inputs. The tied ridge tillage recorded a higher mean of 0.75 me/100g while the conventional tillage had a lower mean of 0.71 me/100g. Intercrop between sorghum and green gram had the highest mean of 0.83 me/100g while the sole green gram recorded the lowest mean of 0.64 me/100g just like in copper. HMHF had the highest mean of 0.83 me/100g while the plots with full fertilizer had the lowest mean of 0.61 me/100g. The interactions had no significant difference (p> 0.05) (Table 4.4).

4.4.11 Zinc (Zn)

Results of the soil analysis revealed that treatments impacted differently in Zinc from one season to the other (Table 4.4). The soil-extracted Zn values were significant due to soil fertility management (Fig. 4.6 B), while other factors and interactions were not significant (Fig. 4.6 A, B). The tied-ridging system recorded a lower soil Zn, relative to conventional tillage. For soil fertility management practices, the control was significantly lower in Zn than all other treatments, which were similar (Fig. 4.6 B). In relation to cropping system, the green gram system recorded the highest soil Zn (3.99), followed by sorghum (3.70) and the intercrop system (3.34).

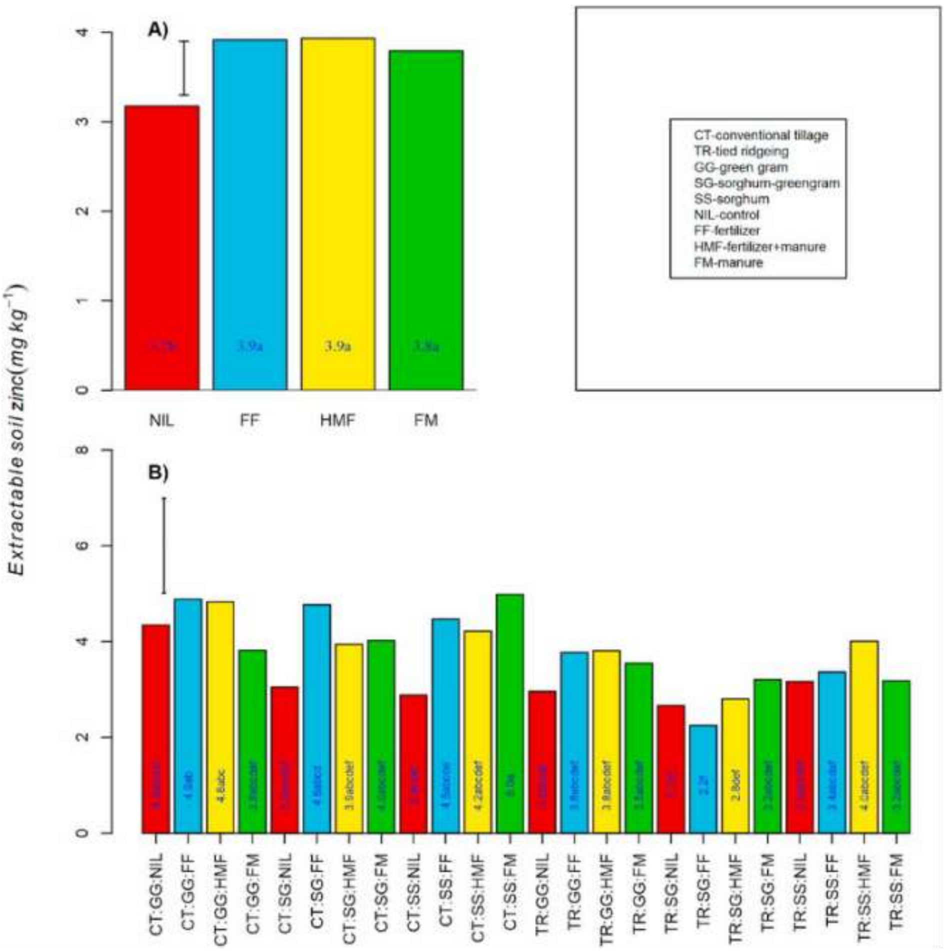

Figure 4.6: Soil tillage, crop system, and fertility management effects on soil Zn. Means followed by the same letters are no significant. Least significant differences are presented as error bars (A,-LSD-soil fertility management, B-Tillage*Cropping, C-Tillage*crop*soil fertility management interaction).

4.5 Sorghum as influenced by tillage and fertility inputs

4.5.1 Leaf chlorophyll content

The lowest mean sorghum chlorophyll content of 34.57 µmol m^{-2} was recorded in plots without amendment while for green gram the mean was 38.87 µmol m^{-2} for plots without amendment. Plots applied with both organic as well as inorganic fertilizers had the highest mean readings of 45.80 µmol m^{-2} and 42.93 µmol m^{-2} for sorghum and green grams, respectively (Table 4.5).

Table 4.5: Effects of different soil amendments and intercropping on SPAD in umol m^{-2} of sorghum/ green gram at Siakago, Kenya.

Soil Amendment	Mean SPAD reading				Mean	
	Sorghum		Green grams			
	Sole crop	Intercrop	Sole Crop	Intercrop	Sorghum	Green Grams
	(Mean ± S.E)		(Mean ± S.E)		(Mean ± S.E)	
Full rate FYM	38.12^{a}±0.408	43.13^{b}±0.376	42.62^{a}±0.196	41.20^{a}±0.333	40.63^{b}±0.101	41.91^{b}±0.088
Full rate Inorganic	35.63^{b}±0.145	36.83^{c}±0.145	40.77^{b}±0.187	41.05^{b}±0.058	36.23^{c}±0.145	40.91^{c}±0.110
½ FYM+ ½ Inorganic	39.37^{a}±0.517	45.80^{a}±0.321	42.93^{a}±0.109	42.57^{a}±0.120	42.58^{a}±0.217	42.75^{a}±0.038
Control (no amendment)	34.57^{b}±0.203	35.33^{d}±0.033	38.87^{c}±0.088	38.93^{c}±0.044	34.95^{d}±0.115	38.90^{d}±0.025
SED	0.596	1.31	0.495	0.399	0.942	0.434
P Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with different letters in a column are significantly different at $p \leq 0.05$.

4.5.2 Days to 50% flowering

The two tillage practices (tied ridges and conventional) did not significantly ($p > 0.05$) affect the days to flowering (Table 4.6). Table 4.6 shows that regardless of the season, there was not a statistically ($p > 0.05$) significant difference between the various cropping strategies. There were no differing responses of the sorghum days to 50% flowering to varying soil amendments (Table 4.6). In a similar trend, interactions between fertilizer, cropping and tillage system did not have a significant ($p > 0.05$) effect (Table 4.6).

Table 4.6: Sorghum Days to 50% flowering under different soil amendments, cropping systems and tillage practices at Siakago, Embu County

Treatment	Cropping season				
	SR 2018	LR 2019	SR 2019	SR 2020	All Seasons Mean
			(Mean ± S.E)		
Tied ridge	62.33^a±1.61	42.33^a±1.61	59.46^a±0.52	58.04^a±0.44	54.71^a±0.84
Conventional tillage	60.71^a±0.85	40.71^a±0.85	60.21^a±0.23	58.00^a±0.51	53.88^a±0.40
P value	0.377	0.377	0.196	0.951	0.5275
Full fertilizer at 60 kg DAP ha^{-1}	61.42^a±2.01	41.42^a±2.02	59.17^a±0.92	57.83^b±0.42	54.95^a±1.12
Full FYM at 5.0 t ha^{-1}	62.17^a±0.99	42.17^a±0.99	60.42^a±0.26	57.08^{bc}±0.31	55.45^a±0.50
Half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1}	62.75^a±2.67	42.75^a±2.68	60.50^a±0.36	61.08^a±0.23	55.52^a±1.31
Unamended check (control)	59.75^a±1.18	39.75^a±1.19	59.25^a±0.48	56.08^c±0.57	52.92^a±0.68
P value	0.6866	0.2461	1	<0.001	0.5777
Sole sorghum cropping system	60.46^a±0.87	40.46^a±0.87	59.83^a±0.42	57.67^a±0.52	54.60^a±0.44
Intercrop sorghum cropping system	62.58^a ±1.59	42.58^a±1.59	59.83^a±0.39	58.37^a±0.42	55.84^a±0.81
P value	0.2461	0.6866	0.1925	0.2971	0.2808
Fertilizer X Cropping	0.917	0.917	0.717	0.053	0.8824
Fertilizer X Tillage	0.491	0.163	0.670	0.823	0.5068
Fertilizer X Cropping X Tillage	0.360	0.360	0.956	<0.001	0.4237

Means with different letters in a column are significantly different at $p \leq 0.05$.

4.5.3 Plant height (M)

The results of plant height (measured from the ground level to the tip of the longest leaf) is presented below. This parameter was measured because of its importance in determining the grain and stover yields that are achieved in a given crop. The two tillage practices (tied ridges and conventional) did not significantly ($p \leq 0.05$) alter the sorghum plant height (Table 4.7). Table 4.7 shows that regardless of the season, there was not a statistically significant ($p > 0.05$) difference between the various cropping strategies. There were no differing responses of the sorghum days to 50% flowering to varying soil amendments (Table 4.7). In a similar trend, interactions between fertilizer, cropping and tillage system did not have a significant (>0.05) (Table 4.7).

Table 4.7: Sorghum Plant height (m) under different soil amendments, cropping systems and tillage practices at Siakago, Embu County

Treatment	Cropping season				
	SR 2018	LR 2019	SR 2019	SR 2020	All Seasons Mean
			(Mean ± S.E)		
Tied ridge	$1.94^{a}\pm0.05$	$1.80^{a}\pm0.04$	$2.04^{a}\pm0.14$	$1.78^{a}\pm0.12$	$1.83^{a}\pm0.07$
Conventional tillage	$1.78^{a}\pm0.09$	$1.66^{a}\pm0.11$	$1.92^{a}\pm0.15$	$1.55^{a}\pm0.09$	$1.81^{a}\pm0.08$
P value	0.122	0.261	0.560	0.160	0.2634
Full fertilizer at 60 kg DAP ha^{-1}	$2.00^{a}\pm0.05$	$1.87^{a}\pm0.04$	$1.91^{ab}\pm0.19$	$1.59^{ab}\pm0.16$	$1.84^{a}\pm0.09$
Full FYM at 5.0 t ha^{-1}	$1.98^{a}\pm0.04$	$1.85^{a}\pm0.03$	$2.15^{ab}\pm0.14$	$1.76^{ab}\pm0.13$	$1.94^{a}\pm0.06$
Half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1}	$2.07^{a}\pm0.04$	$1.91^{a}\pm0.04$	$2.37^{a}\pm0.22$	$1.97^{a}\pm0.17$	$2.08^{a}\pm0.10$
Unamended check (control)	$1.39^{b}\pm0.13$	$1.31^{a}\pm0.19$	$1.48^{b}\pm0.17$	$1.34^{b}\pm0.12$	$1.42^{b}\pm0.07$
P value	<0.001 ***	0.833	<0.001 ***	0.0333 *	<0.001 ***
Sole sorghum cropping system	$1.86^{a}\pm0.08$	$1.75^{a}\pm0.08$	$2.14^{a}\pm0.16$	$1.89^{a}\pm0.12$	$1.93^{a}\pm0.08$
Intercrop sorghum cropping system	$1.86^{a}\pm0.07$	$1.72^{a}\pm0.09$	$1.81^{a}\pm0.12$	$1.44^{b}\pm0.08$	$1.80^{a}\pm0.06$
P value	0.991	0.825	0.876	0.0036 **	0.1674
Fertilizer X Cropping	0.815	0.942	0.127	0.062	0.6228
Fertilizer X Tillage	0.0065**	0.751	0.227	0.508	0.2779
Fertilizer X Cropping X Tillage	0.3001	0.7477	0.664	0.3294	0.376

Means with different letters in a column are significantly different at $p \leq 0.05$.

4.5.4 Sorghum biomass

The biomass yield was not significantly ($p \leq 0.05$) impacted by the various treatments (Table 4.8). However, conventional tillage (flat planting) gave 4-22% higher dry biomass yield in three consecutive seasons compared to tied ridging (Table 4.8). Intercropped plots produced significantly lower ($p \leq 0.05$) biomass across all seasons (Table 4.8). On average, these yields were 7% lower than those of the sole cropped plots. On fertilizer application, sorghum responded differently to varying soil amendments. In each of the four seasons, the plots applied with either organic or inorganic fertilizer yielded considerably ($p \leq 0.05$) better yields than the unamended plots, which resulted in a 40-70% increase in the amount of sorghum biomass produced (Table 4.8). This was the case regardless of which treatment was used. The interactions between the treatments did not significantly (p ≤0.05) alter the biomass of sorghum; that is fertilizer and tillage nor fertilizer, cropping system and tillage except the fertilizer and cropping during the SR 2020 (Table 4.8).

Table 4.8: Sorghum biomass yields (Mg ha^{-1}) under various soil amendments, cropping systems and tillage practices at Siakago, Embu County.

Treatment	Cropping season				
	SR 2018	LR 2019	SR 2019	SR 2020	All Seasons Mean
			(Mean ± S.E)		
Tied ridge	6.71^{a}±0.25	6.03^{a}±0.40	4.73^{a}±0.47	4.67^{a}±0.20	5.53^{a}±0.27
Conventional tillage	7.04^{a}±0.29	6.52^{a}±0.42	5.90^{a}±0.44	4.64^{a}±0.21	6.03^{a}±0.28
P value	0.3825	0.4023	0.0766	0.9416	0.2166
Full fertilizer at 60 kg DAP ha^{-1}	7.68^{a}±0.34	7.67^{a}±0.39	6.71^{a}±0.54	4.69^{a}±0.33	6.69^{a}±0.28
Full FYM at 5.0 t ha^{-1}	6.66^{ab}±0.30	6.42^{a}±0.28	5.63^{a}±0.46	4.70^{a}±0.19	5.85^{a}±0.20
Half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1}	7.34^{a}±0.43	7.36^{a}±0.46	6.11^{a}±0.54	5.48^{a}±0.24	6.57^{a}±0.32
Unamended check (control)	5.82^{b}±0.18	3.64^{b}±0.26	2.81^{b}±0.51	3.75b±0.15	4.01^{b}±0.18
P value	0.0012	<0.001	<0.001	<0.001	<0.001
Sole sorghum cropping system	7.25^{a}±0.24	6.42^{a}±0.42	5.70^{a}±0.46	4.62^{a}±0.21	6.00^{a}±0.28
Intercrop sorghum cropping system	6.49^{b}±0.28	6.13^{a}±0.40	4.92^{b}±0.47	4.69^{a}±0.21	5.56^{a}±0.28
P value	0.0449	0.2415	<0.001	0.8326	0.2711
Fertilizer X Cropping	0.7732	0.8375	0.7687	0.0281 *	0.9878
Fertilizer X Tillage	0.9421	0.4442	0.3684	0.4042	0.9583
Fertilizer X Cropping X Tillage	0.104	0.0511	0.7032	0.4717	0.0781

Means with different letters in a column are significantly different at p ≤ 0.05.

4.5.5 Sorghum grain yield

Practicing the two tillage practices (Tied ridges and conventional) did not significantly (p>0.05) affect sorghum grain yields (Table 4.9). However, conventional tillage gave 5-10% higher grain yield in four seasons under fertilized and non-fertilized plots compared to tied ridging (Table 4.9). Intercropping resulted in a significant ($p \leq 0.05$) decrease in the amount of sorghum grain produced throughout each season (Table 4.9). There were differing sorghum grain yield responses to varying soil amendments. All fertilized plots (irrespective of the treatment) gave significantly ($p \leq 0.05$) higher sorghum grain yields than the unfertilized plots across the four seasons (Table 4.9). In most cases, fertilization led to a forty percent to seventy percent increase in sorghum grain yields (Table 4.9). It was found in Table 4.9 that interactions between fertilizer and cropping systems, fertilizer and tillage, and fertilizer, cropping systems, and tillage did not substantially alter grain yield ($p > 0.05$).

Table 4.9: Sorghum grain yields (Mg ha-^{1}) under various soil amendments, cropping systems and tillage practices at Siakago, Embu County.

Treatment	Cropping season				
	SR 2018	LR 2019	SR 2019 (Mean ± S.E)	SR 2020	All Seasons Mean
Tied ridge	3.01^{a}±0.11	2.66^{a}±0.17	2.19^{a}±0.18	2.04^{a}±0.11	2.48^{a}±0.12
Conventional tillage	3.17^{a}±0.13	2.98^{a}±0.15	2.33^{a}±0.17	2.05^{a}±0.10	2.63^{a}±0.11
P value	0.3545	0.1563	0.5772	0.9355	0.3258
Full fertilizer at 60 kg DAP ha^{-1}	3.47^{a}±0.15	3.53^{a}±0.17	2.81^{a}±0.18	2.07^{a}±0.14	2.97^{a}±0.11
Full FYM at 5.0 t ha^{-1}	3.05^{ab}±0.13	2.82^{b}±0.09	2.29^{a}±0.19	2.17^{a}±0.13	2.59^{b}±0.07
Half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1}	3.30^{a}±0.18	3.09^{ab}±0.12	2.71^{a}±0.16	2.36^{a}±0.15	2.86^{ab}±0.10
Unamended check (control)	2.56^{b}±0.09	1.84^{c}±0.15	1.23^{b}±0.19	1.59^{b}±0.06	1.80^{c}±0.08
P value	<0.001	<0.001	<0.001	<0.001	<0.001
Sole sorghum cropping system	3.24^{a}±0.11	2.84^{a}±0.17	2.36^{a}±0.17	2.02^{a}±0.09	2.61^{a}±0.10
Intercrop sorghum cropping system	2.95^{a}±0.13	2.80^{a}±0.15	2.16^{a}±0.19	2.07^{a}±0.11	2.50^{a}±0.11
P value	0.09599	0.3456	0.4364	0.7104	0.4695
Fertilizer X Cropping	0.8725	0.779	0.1915	0.4492	0.5287
Fertilizer X Tillage	0.9965	0.6172	0.2466	0.3286	0.9393
Fertilizer X Cropping X Tillage	0.0991	0.8452	0.5901	0.8617	0.2741

Means with different letters in a column are significantly different at $p \leq 0.05$.

4.5.6 Sorghum harvesting index

The two tillage practices (tied ridges and conventional) did not significantly ($p > 0.05$) alter the harvest index, with the exception of the SR 2019 (Table 4.10). This season received the highest rainfall at 1383 mm (Figure 4.1). Table 4.10 shows that regardless of the season, there was not a statistically significant ($p > 0.05$) difference between the various cropping strategies. There were no differing responses of the sorghum harvesting index to varying soil amendments (Table 4.10). In a similar trend, interactions between fertilizer and cropping system did not have a significant effect ($p \leq 0.05$) (Table 4.10).

Table 4.10: Sorghum harvesting index under different soil amendments, cropping systems and tillage practices at Siakago, Embu County.

Treatment	Cropping season				
	SR 2018	**LR 2019**	**SR 2019**	**SR 2020**	**All Seasons Mean**
			(Mean ± S.E)		
Tied ridge	$0.44^{a}±0.005$	$0.45^{a}±0.012$	$0.50^{a}±0.033$	$0.44^{a}±0.013$	$0.46^{a}±0.015$
Conventional tillage	$0.45^{a}±0.004$	0.47a±0.013	$0.39^{b}±0.005$	$0.45^{a}±0.011$	$0.44^{a}±0.011$
P value	0.698	0.164	0.003	0.580	0.1021
Full FYM at 5.0 t ha^{-1}	$0.46^{a}±0.003$	$0.45^{a}±0.016$	$0.41^{a}±0.009$	$0.46^{a}±0.018$	0.44^{a} ±0.014
Full fertilizer at 60 kg DAP ha^{-1}	$0.45^{a}±0.006$	$0.46^{a}±0.015$	$0.44^{a}±0.041$	$0.44^{a}±0.017$	$0.45^{a}±0.015$
Half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1}	$0.45^{a}±0.002$	$0.43^{a}±0.017$	$0.48^{a}±0.050$	$0.43^{a}±0.017$	$0.45^{a}±0.014$
Unamended check (control)	$0.44^{a}±0.010$	$0.49^{a}±0.017$	$0.47^{a}±0.036$	$0.42^{a}±0.015$	$0.45^{a}±0.01$
P value	0.268	0.536	0.508	0.477	0.8035
Sole sorghum cropping system	$0.45^{a}±0.005$	$0.45^{a}±0.013$	$0.44^{a}±0.022$	$0.44^{a}±0.011$	$0.44^{a}±0.012$
Intercrop sorghum cropping system	$0.45^{a}±0.004$	$0.47^{a}±0.011$	$0.46^{a}±0.030$	$0.44^{a}±0.013$	$0.46^{a}±0.014$
P value	0.238	0.256	0.516	0.863	0.2143
Fertilizer X Tillage	0.055	0.917	0.538	0.120	0.2241
Fertilizer X Cropping	0.834	0.902	0.678	0.208	0.2669
Fertilizer X Cropping X Tillage	0.941	0.054	0.974	0.499	0.3147

Means with different letters in a column are significantly different at $p \leq 0.05$.

4.6 Green gram as Influenced by tillage and fertility inputs

4.6.1 Green gram days to 50% flowering

The two tillage practices (tied ridges and conventional) did not significantly ($p \leq 0.05$) alter the days to flowering in Green grams (Table 4.11). Table 4.11 shows that regardless of the season, there was not a statistically significant ($p \leq 0.05$) difference between the various cropping strategies. There were no differing responses of the Green grams' days to 50% flowering to varying soil amendments (Table 4.11). In a similar trend, interactions between fertilizer, cropping and tillage system did not have a significant ($p \leq 0.05$) (Table 4.11).

Table 4.11: Green gram Days to 50% Flowering under different soil amendments, cropping systems and tillage practices at Siakago, Embu County.

Treatment	Cropping season				
	SR 2018	LR 2019	SR 2019	SR 2020	All Seasons Mean
			(Mean ± S.E)		
Tied ridge	34.04^{a}±0.15	36.10^{a}±0.14	34.04^{a}±0.15	33.21^{a}±0.36	34.73^{a}±0.14
Conventional tillage	33.63^{a}±0.13	35.71^{a}±0.13	33.63^{a}±0.13	33.95^{a}±0.39	34.32^{a}±0.12
P value	0.4062	0.5548	0.4062	0.1689	0.3414
Full fertilizer at 60 kg DAP ha^{-1}	33.96^{a}±0.22	36.04^{a}±0.23	33.96^{a}±0.22	34.50^{ab}±0.38	34.65^{a}±0.21
Full FYM at 5.0 t ha^{-1}	33.71^{a}±0.16	35.79^{a}±0.14	33.71^{a}±0.16	33.08^{bc}±0.36	34.40^{a}±0.15
Half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1}	33.63^{a}±0.22	35.88^{a}±0.23	33.63^{a}±0.22	31.83^{c}±0.36	34.38^{a}±0.21
Unamended check (control)	34.04^{a}±0.21	35.92^{a}±0.19	34.04^{a}±0.21	34.92^{a}±0.56	34.67^{a}±0.21
P value	0.4324	0.8534	0.4324	**<0.001**	0.5982
Sole Green gram cropping system	34.17^{a}±0.13	36.14^{a}±0.14	34.17^{a}±0.14	33.96^{a}±0.38	34.83^{a}±0.13
Intercrop Green gram cropping system	33.50^{a}±0.12	35.67^{a}±0.13	33.50^{a}±0.12	33.21^{a}±0.38	34.22^{a}±0.11
P value	0.5678	0.8943	0.5159	0.1689	0.5842
Fertilizer X Cropping	0.9776	0.669	0.9776	0.4058	0.9473
Fertilizer X Tillage	0.4912	0.516	0.4912	0.1033	0.4859
Fertilizer X Cropping X Tillage	0.7467	0.6758	0.7467	<**0.001**	0.6926

Means with different letters in a column are significantly different at $p \leq 0.05$.

4.6.2 Green gram plant height (M)

The tallest plants were recorded in SR 2019 under tied ridge tillage (0.73 m). Similarly, during the same season under full FYM recorded highest plant height at

0.73 m while intercropped green grams was highest with 0.69 m. The two tillage practices (tied ridges and conventional) did not significantly ($p > 0.05$) alter the plant height in Green grams (Table 4.12). Regardless of the season, there was not a statistically significant ($p>0.05$) difference between the various cropping strategies. There were differing responses of the Green grams plant height to varying soil amendments in SR 2018 (Table 4.12). In a similar trend, interactions between fertilizer, cropping and tillage system did not have a significant ($p >0.05$) effect (Table 4.12).

Table 4.12: Green gram Plant Height (M) under different soil amendments, cropping systems and tillage practices at Siakago, Embu County.

Treatment	**Cropping season**				
	SR 2018	**LR 2019**	**SR 2019** **(Mean ± S.E)**	**SR 2020**	**All Seasons Mean**
Tied ridge	0.62^{a}±0.02	0.63^{a}±0.10	0.73^{a}±0.10	0.67^{a}±0.04	0.66^{a}±0.027
Conventional tillage	0.61^{a}±0.03	0.44^{a}±0.03	0.53^{a}±0.04	0.61^{a}±0.03	0.55^{a}±0.061
P value	0.795	0.859	0.073	0.213	0.1017
Full fertilizer at 60 kg DAP ha^{-1}	0.67^{a}±0.03	0.56^{a}±0.12	0.68^{a}±0.12	0.64^{a}±0.03	0.64^{a}± 0.073
Full FYM at 5.0 t ha^{-1}	0.70^{a}±0.02	0.63^{a}±0.11	0.73^{a}±0.11	0.73^{a}±0.05	0.69^{a}±0.069
Half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1}	0.61^{a}±0.03	0.60^{a}±0.13	0.70^{a}±0.13	0.62^{a}±0.05	0.64^{a}±0.069
Unamended check (control)	0.48^{b}±0.02	0.33^{a}±0.03	0.41^{a}±0.6	0.58^{a}±0.04	0.41^{a}±0.037
P value	**<0.001**	0.203	0.146	0.109	0.0572
Sole Green gram cropping system	0.59^{a}±0.03	0.58^{a}±0.03	0.57^{a}±0.11	0.56^{b}±0.03	0.58^{a}±0.063
Intercrop Green gram cropping system	0.63^{a}±0.02	0.48^{a}±0.10	0.69^{a}±0.03	0.72^{a}±0.02	0.60^{a}±0.024
P value	0.293	0.386	0.268	**<0.001**	0.7704
Fertilizer X Cropping	0.951	0.702	0.654	**0.017**	0.587
Fertilizer X Tillage	0.896	0.869	0.884	0.632	0.911
Fertilizer X Cropping X Tillage	0.287	0.715	0.767	0.413	0.6892

Means with different letters in a column are significantly different at $p \leq 0.05$.

4.6.3 Green gram biomass

The green gram biomass results presented in Table 4.13 show that the tied and conventional tillage practices were not significantly ($p >0.05$) different with respect to green gram biomass yields. However, conventional tillage gave 1.4 % and 5% higher green gram biomass yield in SR2018 and LR2019, respectively (Table 4.13). Tied ridges had 3.4 and 7% higher green gram biomass yields in SR2020 and SR2019 (Table 4.13). Intercropped plots produced significantly ($p \leq 0.05$) lower green gram biomass yield across all seasons (Table 4.13). On average, these yields were 20% lower than those of the sole cropped plots. On fertilization, there were differing responses of the green grams crop to varying soil ameliorants. All fertilized plots (irrespective of the treatment) had significantly ($p \leq 0.05$) higher yields compared to unamended check plots in each of the four seasons (Table 4.13). Generally, there was a 30-50% increase in green gram biomass yields due to fertilization (Table 4.13). With regard to the treatments interactions, only the fertilizer and cropping system had significant ($p \leq 0.05$) difference. The green gram biomass was not considerably affected by interactions between; fertilizer and tillage as well as fertilizer, cropping system and tillage.

Table 4.13: Green gram biomass yields (Mg ha^{-1}) under different soil amendments, cropping systems and tillage practices at Siakago, Embu County.

Treatment	Cropping season				
	SR 2018	LR 2019	SR 2019	SR 2020	All Seasons Mean
	(Mean ± S.E)				
Tied ridge	2.81^{a}±0.17	2.64^{a}±0.15	2.97^{a}±0.10	2.89^{a}±0.12	2.81^{a}±0.09
Conventional tillage	2.85^{a}±0.15	2.78^{a}±0.15	2.76^{a}±0.16	2.88^{a}±0.15	2.80^{a}±0.14
P value	0.851	0.474	0.292	0.946	0.9534
Full fertilizer at 60 kg DAP ha^{-1}	3.01^{a}±0.15	2.93^{a}±0.17	3.09^{a}±0.19	2.86^{ab}±0.18	2.97^{a}±0.11
Full FYM at 5.0 t ha^{-1}	3.20^{a}±0.17	2.79^{a}±0.12	2.97^{ab}±0.12	2.97^{a}±0.20	2.99^{a}±0.12
Half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1}	3.04^{a}±0.24	2.98^{a}±0.21	3.06^{a}±0.20	3.37^{a}±0.15	3.11^{a}±0.13
Unamended check (control)	2.09^{b}±0.20	2.15^{b}±0.13	2.33^{b}±0.17	2.34^{b}±0.09	2.23^{b}±0.09
P value	<0.001	0.0029	0.0101	<0.001	<0.001
Sole Green gram cropping system	3.03^{a}±0.18	2.96^{a}±0.14	3.19^{a}±0.13	3.26^{a}±0.12	3.11^{a}±0.12
Intercrop Green gram cropping system	2.64^{b}±0.12	2.45^{b}±0.09	2.54^{b}±0.11	2.52^{b}±0.09	2.54^{b}±0.09
P value	<0.001	<0.001	<0.001	<0.001	<0.001
Fertilizer X Cropping	0.955	0.006	0.204	0.074	0.0054
Fertilizer X Tillage	0.548	0.545	0.250	0.799	0.4908
Fertilizer X Cropping X Tillage	0.938	0.476	0.997	0.482	0.6813

Means with different letters in a column are significantly different at $p \leq 0.05$.

4.6.4 Green gram grain yields

The use of tied ridges and conventional tillage did not significantly ($p \leq 0.05$) alter the yields of green gram (Table 4.14). Conventional tillage produced 1.3 % and 4.2% green gram yields in SR2018 and SR2020, respectively (Table 4.14). Tied ridges had 2.7 % and 4.9% green gram grain yield in LR2019 and SR2019, respectively (Table 4.14). Intercropped plots yielded meaningfully lower ($p \leq 0.05$) green gram grain yield across all seasons. On average, these yields were 10- 40% lower than those of the sole cropped plots. In each of the four growing seasons, the fertilized plots, regardless of the treatment, consistently produced considerably ($p \leq 0.05$) higher yields than the unfertilized control. Generally, use of fertilizer resulted in a 40-60% increase in green gram grain yields (Table 4.14). With regard to the treatments interactions, only the fertilizer and cropping system as well as the fertilizer, cropping system and tillage gave significantly ($p \leq 0.05$) higher interactions during the SR 2019 cropping season that had more rainfall than the other seasons.

Table 4.14: Green gram grain yields (Mg ha $^{-1}$) under different soil amendments, cropping systems and tillage practices at Siakago, Embu County.

Treatment	Cropping season				
	SR 2018	LR 2019	SR 2019	SR 2020	All Seasons Mean
			(Mean ± S.E)		
Tied ridge	1.49^{a}±0.09	1.11^{a}±0.07	1.02^{a}±0.04	1.14^{a}±0.15	1.21^{a}±0.05
Conventional tillage	1.51^{a}±0.08	1.08^{a}±0.06	0.97^{a}±0.05	1.19^{a}±0.16	1.19^{a}±0.06
P value	0.851	0.760	0.495	0.792	0.9942
Full fertilizer at 60 kg DAP ha^{-1}	1.59^{a}±0.08	1.19^{a}±0.08	1.09^{a}±0.06	1.03^{ab}±0.16	1.23^{a}±0.06
Full FYM at 5.0 t ha^{-1}	1.69^{a}±0.09	1.31^{a}±0.08	1.04^{a}±0.04	1.45^{a}±0.25	1.37^{a}±0.05
Half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1}	1.61^{a}±0.12	1.08^{ab}±0.10	1.08^{a}±0.07	1.53^{a}±0.23	1.32^{a}±0.08
Unamended check (control)	1.10^{b}±0.11	0.82^{b}±0.06	0.77^{b}±0.06	0.64^{b}±0.11	0.84^{b}±0.04
P value	<0.001	0.0012	0.0012	0.0081	<0.001
Sole Green gram cropping system	1.60^{a}±0.09	1.22^{a}±0.06	1.08^{a}±0.05	1.61^{a}±0.14	1.38^{a}±0.06
Intercrop Green gram cropping system	1.39^{b}±0.07	0.97^{b}±0.07	0.91^{b}±0.04	0.72^{b}±0.09	1.00^{b}±0.04
P value	0.083	0.007	0.008	<0.00	<0.001
Fertilizer X Tillage	0.547	0.371	0.61	0.916	0.8287
Fertilizer X Cropping	0.954	0.133	0.029	0.100	0.0045
Fertilizer X Cropping X Tillage	0.937	0.285	0.029	0.460	0.3258

Means with different letters in a column are significantly different at $p \leq 0.05$

4.6.5 Green gram harvest index

Conventional and tied ridge tillage practices did not significantly affect the harvest index ($p \leq 0.05$) (Table 4.15). There was no significant ($p \leq 0.05$) difference on the different cropping systems across three seasons except SR 2020 that had significant ($p \leq 0.05$) difference. There were differing responses of the green gram harvesting index to varying soil amendments during LR 2019, SR 2019 and SR 2020. The harvesting index was not significantly affected by interactions between fertilizer X cropping, as well as fertilizer X cropping system X tillage but significantly affected interaction between fertilizers X tillage during the LR 2019 (Table 4.15).

Table 4.15: Green gram harvesting index under different soil amendments, cropping systems and tillage practices at Siakago, Embu County.

Treatment	Cropping season				
	SR 2018	LR 2019	SR 2019 (Mean ± S.E)	SR 2020	All Seasons Mean
Tied ridge	$0.53^{a}±0.003$	$0.42^{a}±0.027$	$0.34^{a}±0.008$	$0.35^{a}±0.037$	$0.43^{a}±0.009$
Conventional tillage	$0.53^{a}±0.004$	$0.39^{a}±0.016$	$0.35^{a}±0.005$	$0.39^{a}±0.036$	$0.42^{a}±0.006$
P value	0.6009	0.3558	0.4241	0.5086	0.8443
Full fertilizer at 60 kg DAP ha^{-1}	$0.53^{a}±0.004$	$0.41^{ab}±0.216$	$0.35^{a}±0.002$	$0.33^{ab}±0.047$	$0.41^{ab}±0.008$
Full FYM at 5.0 t ha^{-1}	$0.53^{a}±0.014$	$0.48^{a}±0.024$	$0.35^{a}±0.006$	$0.44^{a}±0.058$	$0.45^{a}±0.014$
Half manure & fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1}	$0.53^{a}±0.009$	$0.36^{b}±0.215$	$0.35^{a}±0.004$	$0.43^{a}±0.052$	$0.42^{ab}±0.009$
Unamended check (control)	$0.53^{a}±0.003$	$0.38^{ab}±0.023$	$0.33^{a}±0.017$	$0.26^{b}±0.038$	$0.38^{b}±0.006$
P value	0.3762	0.0236 *	0.4885	0.0468*	0.0245 *
Sole Green gram cropping system	$0.53^{a}±0.008$	$0.42^{a}±0.014$	$0.34^{a}±0.008$	$0.47^{a}±0.032$	$0.44^{a}±0.009$
Intercrop Green gram cropping system	$0.53^{a}±0.006$	$0.39^{a}±0.027$	$0.36^{a}±0.003$	$0.27^{b}±0.031$	$0.39^{b}±0.006$
P value	0.1456	0.5891	0.3871	<0.001	0.0035
Fertilizer X Cropping	0.3701	0.8221	0.0562	0.2617	0.4253
Fertilizer X Tillage	0.7283	0.0489 *	0.5919	0.9816	0.5242
Fertilizer X Cropping X Tillage	0.3707	0.5861	0.9757	0.5784	0.4699

Means with different letters in a column are significantly different at $p \leq 0.05$.

4.6.6 Land equivalent ratio (LER)

The results presented in Table 4.16 show the control plots had an LER that was considerably ($p \leq 0.05$) greater than the fertilized plots in SR 2018 and LR 2019. The range in LER across the different seasons was 0.39-1.09. The treatment with half amount of organic and inorganic inputs recorded the lowest LER values of 0.69 while the treatment with no amendment logged the highest with an average of 0.85 (Table 4.16).

Table 4.16: LER under different soil amendments of Sorghum/ green gram at Siakago, Embu County.

SOIL AMENDMENT	SEASONS				
	SR 2018 (Mean ± S.E)	**LR 2019 (Mean ± S.E)**	**SR 2019 (Mean ± S.E)**	**SR 2020 (Mean ± S.E)**	**MEAN (Mean ± S.E)**
Full FYM at 5.0 t ha^{-1}	0.90^{a}±0.15	0.83^{ab}±0.09	0.80^{a}±0.07	0.39^{a} ±0.11	0.73^{a}±0.07
Full fertilizer at 60 kg DAP ha^{-1}	0.77^{a}±0.07	0.77^{ab}±0.04	0.91^{a}±0.15	0.45^{a}±0.12	0.72^{a}±0.04
Half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1}	0.80^{a}±0.21	0.60^{b}±0.08	0.79^{a}±0.17	0.58^{a}±0.09	0.69^{a}±0.13
Unamended check (control)	1.04^{a}±0.16	1.09^{a}±0.17	0.71^{a}±0.14	0.56^{a}±0.13	0.85^{a}±0.07
Mean	0.88	0.82	0.8	0.5	0.75
SE	0.0746	0.092	0.0673	0.0592	0.0557
P Value	0.5789	0.0316 *	0.7892	0.6196	0.5435

Means with different letters in a column are significantly different at $p \leq 0.05$.

CHAPTER FIVE

DISCUSSION

5.1 Rainfall

The results of the cumulative rainfall for the four planting seasons in Siakago, Embu County, Kenya, highlight significant variability in both the distribution and total amount of rainfall received during the long rains (LR) and short rains (SR) periods. These variations in rainfall patterns are crucial as they directly influence soil properties and crop productivity. The SR 2018 season experienced a moderate amount of rainfall, with 36 rainy days between October and December, totaling 380 mm. However, the subsequent months of January and February 2019 were relatively dry, which could have impacted the soil moisture availability for the crops during their critical growth phases.

In contrast, the LR 2019 season, from April to June, recorded 905 mm of rainfall over 30 days. This period saw significant rainfall in April and May, but minimal precipitation in June and July. The short duration of the LR 2019 season and the concentrated rainfall could lead to periods of waterlogging followed by potential moisture stress during the drier months, affecting the root development and nutrient uptake of the crops. The SR 2019 season was notably wetter, with an extended period of rainfall from October 1st to February 26th, 2020, resulting in 1383 mm of rainfall over approximately 85 rainy days. This prolonged and substantial rainfall likely ensured consistently saturated soil conditions, which could benefit crop growth but also pose risks of nutrient leaching and waterlogging, affecting the crop yields.

The SR 2020 season exhibited high rainfall in November but saw minimal rainfall from December to February, accumulating a total of 696 mm. This pattern of high initial rainfall followed by a dry spell could lead to an initial boost in crop establishment but might stress the crops later due to reduced soil moisture availability. The cumulative rainfall data across these seasons reveal a wide range, from 380 mm in SR 2018 to 1383 mm in SR 2019, demonstrating the need for adaptive management strategies in tillage and fertilizer application to optimize soil health and crop productivity under variable climatic conditions. The insights gained from these rainfall patterns are essential for developing effective agronomic practices to enhance the resilience of sorghum and green gram production in the region.

5.2 Soil Properties

The research examined the consequences of various tillage practices, cropping systems, and fertility inputs on soil pH, total organic carbon (TOC), and total nitrogen (TN) in a 4 season study. The findings showed that the soil pH was somewhat acidic, with a mean pH of 5.42 in the tied ridge treatment and 5.38 in the conventional tillage treatment. The soil pH was highest in the plots with half manure and half fertilizer (HMHF), with a mean pH of 5.44. The study found that the TOC was highest in the plots with HMHF, with a mean of 0.58%. The TOC was also highest in the sole green gram cropping system, with a mean of 0.50%. The study discovered that tillage practice had no significant impact on TOC, but cropping systems and fertility inputs did have a significant impact. The findings were in agreement with Njiru *et al*. (2023) who found that tillage did not influence soil organic matter distribution in Eastern semi-arid farm systems significantly. Similarly, Gichimu *et al*.(2023) found that soil conservation strategies and fertility management reduced soil nutrient losses and soil organic carbon, which explained the slight increase in soil carbon under the tied-ridging system.

The study also found that the TN was highest in the plots with HMHF, with a mean of 0.05%. The TN was also highest in the sole green gram cropping system, with a mean of 0.05%. The study also found that tillage practice had no significant impact on TN, but cropping systems and fertility inputs did have a significant impact. Furthermore, the study revealed that the interaction between tillage practice and cropping system had a significant impact on TOC and TN. In the present study, tied ridge treatment with green gram cropping system had the highest TOC and TN. Amrita *et al*. (2022) observed that soil microbiological properties were significantly improved in fields where green-gram was included. This is likely to have improved the soil total carbon and total nitrogen concentrations, particularly under tied-ridge treatments which enhanced conservation of soil nutrients. The findings of the study in relation to tied-ridging in semi-arid areas were consistent with findings of several authors who recorded that tied-ridging and integrated soil fertility management practices were needed to improve soil fertility and crop performance (Kugedera *et al.* 2022).

In addition, the study investigated the effects of various tillage practices, cropping systems, and fertility inputs on extractable phosphorus (P), potassium (K+), calcium (Ca), magnesium (Mg), iron (Fe), copper (Cu), manganese (Mn), and zinc (Zn) in a long-term study. The results showed that the extractable P was higher in the tied ridge treatment, with a mean of 7.99 ppm, compared to the conventional tillage treatment, with a mean of 6.35 ppm. The study also found that the extractable P was highest in the sole green gram cropping system, with a mean of 7.56 ppm. This result contrasts with Somasundaram *et al*. (2020) who reported greater soil available P in fields with lower tillage intensity including shallow tillage and no-tillage systems.

The study also found that the extractable K+ was higher in the tied ridge treatment, with a mean of 0.41 me/100g, compared to the conventional tillage treatment, with a mean of 0.37 me/100g. The study also found that the extractable Ca was higher in the conventional tillage treatment, with a mean of 5.34 me/100g, compared to the tied ridge treatment, with a mean of 4.90 me/100g. Furthermore, the study found that extractable Mg was higher in the conventional tillage treatment, with a mean of 1.71 me/100g, compared to the tied ridge treatment, with a mean of 1.31 me/100g. The study also found that the extractable Fe was higher in the conventional tillage treatment, with a mean of 49 ppm, compared to the tied ridge treatment, with a mean of 37.36 ppm.

The current study also found that the extractable Cu was higher in the tied ridge treatment, with a mean of 5.39 ppm, compared to the conventional tillage treatment, with a mean of 4.29 ppm. The extractable Mn in the current study was higher in the tied ridge treatment, with a mean of 0.75 me/100g, compared to the conventional tillage treatment, with a mean of 0.71 me/100g. The extractable Zn was higher in the tied ridge treatment, with a mean of 3.99 ppm, compared to the conventional tillage treatment, with a mean of 3.70 ppm. Conventional tillage systems can lead to compaction of soils, resulting to increased soil bulk density which can reduce soil aeration and water infiltration, limiting zinc availability (Singh *et al.,* 2020). Soil fertility management influence on soil Zn was partly expected because of the effects of input application practices on soil organic carbon, which influenced the distribution of soil micronutrient availability (Kiboi *et al.* 2021). The finding was consistent with Kumar *et al.* (2014) who observed an increase in several macronutrients and micronutrients (including potassium, magnesium, iron, manganese, zinc and boron) after mulching soils during a 3-year experiment. Dhaliwal *et al.* (2019) recommended that organic soil amendments including compost, and farmyard manure (FYM), are beneficial in providing some amounts of essential micronutrients for plant growth and development.

5.3 Leaf Chlorophyll Content

In the current study, the effects of different soil amendments and intercropping on the leaf chlorophyll content of sorghum and green gram were examined. The study demonstrated that the leaf chlorophyll content was considerably influenced by the intercropping system and the type of soil amendment used. The study found that the plots without any soil amendment had the lowest mean leaf chlorophyll content, with values of 34.57 umol m^{-2} for sorghum and 38.87 umol m^{-2} for green gram. In contrast, the plots that received both organic and inorganic fertilizers had the highest mean leaf chlorophyll content, with values of 45.80 umol m^{-2} for sorghum and 42.93 umol m^{-2} for green gram.

The results also showed that the intercropping system had a significant effect on the leaf chlorophyll content. The plots that received sole cropping had lower mean leaf chlorophyll content compared to the plots that received intercropping. This implies that intercropping may positively impact the leaf chlorophyll content of crops. This is in agreement with Muoni *et al*. (2022). Additionally, the study found that the type of soil amendment had a considerable influence on the leaf chlorophyll content. The plots that received full rate FYM had higher mean leaf chlorophyll content compared to the plots that received full rate inorganic fertilizer. This suggests that organic amendments may have a more positive effect on the leaf chlorophyll content compared to inorganic fertilizers. Similar results of increase in total chlorophyll content due to fertilizer application was reported by Kaur *et al*. (2024). This underscores the value of fertilization in improving sorghum yields.

5.4 Sorghum and Green gram Days to 50% flowering

The study examined the effects of different tillage practices, cropping systems, and fertilizer applications on the days to 50% flowering in sorghum. The results showed that the two tillage practices (tied ridges and conventional) did not significantly affect the days to flowering in sorghum. This suggests that tillage practices did not significantly affect the flowering period of the crop. The study also found that the different cropping seasons (SR 2018, LR 2019, and SR 2019) did not significantly affect the days to 50% flowering in sorghum. This implies that the flowering period of the crop was not influenced by the season.

The current study found that the different fertilizer applications (full fertilizer, full FYM, half manure and fertilizer, and unamended) did not significantly affect the days to 50% flowering in sorghum. This suggests that the fertilizer applications did not have a significant impact on the flowering period of the crop. The study also examined the interactions between fertilizer, cropping system, and tillage system. It showed that there were no significant interactions between these factors and the days to 50% flowering in sorghum. This suggests that the effects of the different factors on the flowering period of the crop were not influenced by the other factors.

The study also examined the effects of different tillage practices, cropping systems, and fertilizer applications on the days to 50% flowering in green gram. The results showed that the two tillage practices (tied ridges and conventional) did not significantly affect the days to flowering in green gram. This suggests that the tillage practices did not have a significant impact on the flowering period of the crop. The study also found that the different cropping seasons (SR 2018, LR 2019, and SR 2019) did not significantly affect the days to 50% flowering in green gram. This implies that the flowering period of the crop was not influenced by the season. This contrasts with Musyimi (2022) found highest number of days to 50% flowering in tied ridges while lowest number of days were recorded on no ridges.

The results also showed that the different fertilizer applications (full fertilizer, full FYM, half manure and fertilizer, and unamended) did not significantly affect the days to 50% flowering in green gram. This suggests that the fertilizer applications did not have a significant impact on the flowering period of the crop. This is in contrast with Zhang *et al*. (2023) who found that fertilizer application had an impact on the days to flowering. The study also examined the interactions between fertilizer, cropping system, and tillage system. The results showed that there were no significant interactions between these factors and the days to 50% flowering in green gram. This suggests that the effects of the different factors on the flowering period of the crop were not influenced by the other factors.

5. 5 Sorghum and Green Gram Plant Height

The research investigated the consequences of different soil amendments, planting systems, and plowing methods on the height of green gram plants. The study revealed that the tallest green gram plant was observed in SR 2019 with a height of 0.73 m under tied ridge tillage. Additionally, the highest height was also documented under full FYM fertilizer at 0.73 m and intercropped green grams at 0.69 m during the same growing season. This is in agreement with Muindi (2019) who found combined application of zinc, farmyard manure, and starter NP significantly ($P \leq 0.05$) improved mean plant height. FYM + soil zinc recorded the highest plant height while control recorded the lowest.

In the present study, the two tillage practices (tied ridges and conventional) did not significantly alter the plant height of green gram. Moreover, there was no statistically significant discrepancy between the various planting techniques, regardless of the season. These results are in line with that of Musyimi (2022) who found a decrease in plant height under no ridges.

The study's results also indicated that green gram plant height responded differently to different soil amendments in SR 2018. However, the interactions between fertilizer, cropping, and tillage system did not have a significant effect on plant height. The study highlights the importance of considering the interactions between different factors, such as soil amendments, cropping systems, and tillage practices, to optimize the growth and productivity of green gram. The findings suggest that tied ridge tillage and intercropping with other crops may be effective strategies for improving the plant height and overall productivity of green gram. Arshad *et al.* (2023) found sorghum plant height to decrease under soybean intercrop by (-4%) to (-8%) and increase under mung-bean intercropping by (+4) to (+20%). This is in agreement with Muindi (2019) who found combined application of zinc, farmyard manure, and starter NP significantly ($P \leq 0.05$) improved mean plant height. FYM + soil zinc recorded the highest plant height while control recorded the lowest.

5.6 Sorghum Biomass and Grain yield

The study's findings on green gram biomass and grain yields demonstrated that tillage practices did not significantly affect the yields, except for SR 2020 where tied ridges had a higher biomass yield. However, the conventional tillage practice had a higher biomass yield in SR 2018 and LR 2019. The intercropped plots had significantly lower biomass and grain yields compared to the sole-cropped plots, suggesting that intercropping may not be suitable for green gram production in the study area.

The study also showed that fertilized plots, regardless of the treatment, had significantly greater biomass and grain yields compared to the unfertilized control. This implies that the application of fertilizers may have had a positive impact on the yield and productivity of the green gram crop. These results are in agreement with Ameen *et al.* (2017) that sorghum biomass increased with fertilizer rate up to 60 kg DAP ha^{-1}. The interaction between fertilizer and planting system had a significant impact on the biomass and grain yield of green gram, suggesting that the type of planting system used may affect the crop's response to fertilizer application. Similarly, Githunguri *et al*. (2016) found fertilized sorghum producing higher grain yields than those grown without fertilizers.

The results of the sorghum biomass study showed that the biomass yield was not significantly impacted by the various treatments. However, conventional tillage gave 4-22% higher dry biomass yield in three consecutive seasons compared to tied ridging. This corroborates the findings of Rurinda *et al.* (2014), who observed that waterlogging inhibits the growth of sorghum. In a similar vein, the findings of the current study agree with those of Githunguri *et al.* (2016) who reported 25% higher sorghum biomass yield under conventional tillage compared to tied ridges in Makueni ASALs Kenya.

Intercropped plots produced significantly lower biomass across all seasons. On average, these yields were 7% lower than those of the sole-cropped plots. The results also showed that the interactions between the treatments did not significantly alter the biomass of sorghum; that is, fertilizer and tillage nor fertilizer, cropping system and tillage except the fertilizer and cropping during the SR 2020. This is in line with the findings of Neeraj *et al.* (2023), who obtained the highest sorghum grain yield under sole sorghum, followed by sorghum and green gram intercrop and Tanwar *et al*. (2014) who found less than half reduction in sorghum yield on intercropping.

The sorghum grain yield study results indicated that practicing the two tillage practices (Tied ridges and conventional) had an insignificant effect on the sorghum grain yields. However, conventional tillage gave 5-10% higher grain yield in four seasons under fertilized and non-fertilized plots compared to tied ridging. Intercropping resulted in a significant decrease in the amount of sorghum grain produced throughout each season. The findings of the present study on decreased sorghum and green gram yields differ from those of Ren *et al*. (2014) and Yu *et al*. (2016) who found intercropping increasing cereal yields while not affecting legume yields in meta-analyses of intercropping systems. All fertilized plots gave significantly higher sorghum grain yields than the unfertilized plots across the four seasons. Kugedera *et al,* (2018) who found that a combination of cow dung and mineral fertilizer led to an increase in the grain production of sorghum. The interactions between fertilizer and cropping systems, fertilizer and tillage, and fertilizer, cropping systems, and tillage did not substantially alter grain yield.

The study results indicated that the application of fertilizers may have had a positive impact on the yield as well as the overall green gram productivity, and that the type of cropping system used may also have an impact on the response of the crop to fertilizer application. The study also found that intercropping may not be suitable for green gram production in the study area. The results of the sorghum biomass and grain yield studies suggest that conventional tillage may be a better option than tied ridging, and that fertilization can significantly increase sorghum yields.

5.7 Sorghum harvesting index

The results of the sorghum harvesting index study showed that the two tillage practices did not significantly alter the harvest index, except for SR 2019. The season received the highest rainfall at 1383 mm. There was statistically insignificant difference between the various cropping strategies, and the interactions between fertilizer and cropping system had an insignificant effect on the sorghum harvesting index. Studies done by Nyamadzawo *et al*. (2013), reported significant interactions between fertilizers and tillage on sorghum harvest index. The findings of the current study are therefore in contrast to those reported by Ngetich *et al.* (2014), who observed that sorghum grown under moisture conservation practice had the highest harvesting index of 0.47.

5.8 Green gram Biomass and Grain yields

The results presented in Table 4.13 and 4.14 show that the green gram biomass and grain yields were not significantly affected by the tillage practices, with the exception of SR 2020, where tied ridges had a higher biomass yield. However, the results also show that the conventional tillage practice had a higher biomass yield in SR 2018 and LR 2019. The results also show that the intercropped plots had a significantly lower biomass and grain yield compared to the sole cropped plots. This suggests that the intercropping system may not be suitable for green gram production in the study area. This is in agreement with Faridvand *et al*. (2022) whose results showed sole cropping produced the highest yield in mung bean.

The results also show that the fertilized plots, regardless of the treatment, had a significantly higher biomass and grain yield compared to the unfertilized control. This suggests that the application of fertilizers may have had a positive impact on the yield and productivity of the green gram crop. This is in agreement with Babak *et al.* (2021) who observed that Nitrogen fertilizer application positively influenced mung bean yield under reduced tillage systems. The results also show that the interaction between fertilizer and cropping system had a significant effect on the biomass and grain yield of green gram. This suggests that the type of cropping system used may have an impact on the response of the crop to fertilizer application.

The results also show that the interaction between fertilizer, cropping system, and tillage had no significant effect on the biomass and grain yield of green gram. This suggests that the type of tillage practice used may not have an impact on the response of the crop to fertilizer application. Therefore, the results suggest that the application of fertilizers may have had a positive impact on the yield and productivity of the green gram crop, and that the type of cropping system used may also have an impact on the response of the crop to fertilizer application.

5.9 Green gram harvest index

The results presented in Table 4.15 show that the harvest index of green gram was not significantly affected by conventional and tied ridge tillage practices. This suggests that the tillage practices did not have a significant impact on the yield and productivity of the green gram crop. The results also show that there was no significant difference in the harvest index across the different cropping systems except for SR 2020, which had a significant difference. This suggests that the cropping system may have had an impact on the yield and productivity of the green gram crop in SR 2020.

The results also show that the harvest index was not significantly affected by the interactions between fertilizer and cropping system, as well as fertilizer and cropping system and tillage. However, the harvest index was significantly affected by the interaction between fertilizers and tillage during LR 2019. The results also show that the harvest index varied significantly across the different seasons, with the highest value recorded in SR 2020 and the lowest value recorded in SR 2018. This suggests that the harvest index may have been affected by factors such as weather conditions, soil moisture, and pest and disease pressure.

In the present study, full FYM at 5.0 t ha^{-1} had a relatively higher harvest index of 0.45, while the treatment with no amendment had a relatively lower harvest index of 0.38. This suggests that the application of FYM may have had a positive impact on the yield and productivity of the green gram crop. Overall, the results suggest that the harvest index of green gram was not significantly affected by tillage practices, but was affected by the interactions fertilizers and tillage. The findings of the current study are therefore in contrast to those reported by Ngetich *et al.* (2014), who observed that green gram grown under moisture conservation practice had the highest harvesting index of 0.47. The present study results on significant interactions between fertilizers and tillage on green gram harvest index agree with those of Nyamadzawo *et al*. (2013).

5.10 Land Equivalent Ratio (LER)

The results presented in Table 4.16 show that the control plots had a significantly higher Land Equivalent Ratio (LER) compared to the fertilized plots in SR 2018 and LR 2019. This suggests that the control plots had a higher yield and productivity compared to the plots with fertilizers and manure amendments. The range in LER across the different seasons was found to be 0.39-1.09, indicating that the LER values varied significantly across the different seasons. The treatment with half amount of organic and inorganic inputs recorded the lowest LER values of 0.69, while the treatment with no amendment logged the highest with an average of 0.85.

The results also show that the treatment with full fertilizer at 60 kg DAP ha^{-1} had a relatively lower LER value of 0.77 compared to the control plots. This suggests that the fertilizer application may not have had a significant impact on the yield and productivity of the sorghum and green gram crops. On the other hand, the treatment with full FYM at 5.0 t ha^{-1} had a relatively higher LER value of 0.90 in SR 2018 and 0.83 in LR 2019. This suggests that the application of FYM may have had a positive impact on the yield and productivity of the crops. This is in agreement with Neereaj *et al*. (2023) who realized increased rates of FYM led to a higher LER with best performance seen at 20 t ha^{-1} and lowest in control group. The results also show that the treatment with half manure and fertilizer at 2.5 t ha^{-1} manure + 30 kg DAP ha^{-1} had a relatively lower LER value of 0.69. This suggests that the combination of manure and fertilizer may have had a significant impact on the yield and productivity of the crops. These values are lower than those of Tanwar *et al*. (2014), who found >1 LER in all sorghum and green grams intercropping treatments. Degu *et al.* (2022)'s study showed that Sorghum-mung bean intercropping demonstrated biological efficiency with the best results seen in the 1:2 row arrangement.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The study findings provide important perspectives related to soil macro nutrients and micro-nutrient fertility in semi-arid small- scale farming systems. Tied-ridging contributed to preliminary increments in the soil organic carbon and nitrogen concentrations. The use of both organic and inorganic fertilizer has some effect on nutrient levels in the soil and on the growth and yield of both sorghum and green gram crops over the growing seasons of this study. The combined use of organic and inorganic fertilizer results in higher yields in both sorghum and green gram compared to the use of one type of fertilizer alone.

The conclusions on specific objectives.

1. Objective 1: This study suggests that both convention and tied-ridge tillage practices can influence the availability of specific soil nutrients. Tied-ridging in particular contributed to preliminary increments in the soil organic carbon and nitrogen concentrations.

2. Objective 2: This study did not find any significant advantage of the tied ridge mechanization over conventional tillage with respect to sorghum and green gram agronomical growth.

3. Objective 3: The study suggests that a combination of organic and inorganic fertilizers can improve soil pH, total organic carbon, and total nitrogen when compared to the application of either inorganic or organic fertilizer alone.

4. Objective 4: The balanced use of combined organic and inorganic amendments lead to improved plant health and sorghum and green gram productivity.

6.2 Recommendation

1. This study can be done over a longer time duration for better evaluation of the effect of tillage impacts on soil organic carbon in the semi-arid farming system.
2. The management strategies in dry land farming systems that integrate manure and fertilizers can be studied over longer periods of time.
3. Intercropping sorghum and Green gram should be studied further
4. There is need for long term trials in farmers' fields where there is diverse soil physical and chemical properties.

5. A study should also be done under rain fed situations because most farmers depend on rains for their crops.

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