ASSESSING EFFECTS OF *ZAI* PIT WITH INTEGRATED SOIL FERTILITY MANAGEMENT ON SORGHUM YIELDS AND SOIL PROPERTIES IN KITUI COUNTY, KENYA.

KEBENEI MERCY CHERUTO
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DECLARATION

I understand that plagiarism is an offence and I therefore declare that this thesis is my original work and has not been presented to any other institution for any other award.

Signature: ________________________ Date:_______________________

Kebenei Mercy Cheruto

(REG. NO: B502/MAI/30002/2018)

This thesis proposal has been submitted for examination with our approval as University Supervisors

Signature: ________________________ Date: ___________________

Prof. Monica Mucheru-Muna

Department of Environmental Science and Education

Kenyatta University

Signature: ________________________ Date: ___________________

Dr. Felista Muriu-Ng'ang'a

Department of Environmental Science and Land Resource Management

South Eastern Kenya University

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ABBREVIATIONS AND ACRONYMS

ANOVA	**:**	Analysis of Variance
ASALs	**:**	Arid and Semi-Arid Lands
C	**:**	Carbon
DOC	**:**	Dissolved Organic Carbon
EC	**:**	Electrical Conductivity
FAO	**:**	Food and Agriculture Organization
FURP	**:**	Fertilizer Use Recommendation Project
GoK	**:**	Government of Kenya
IPCC	**:**	Intergovernmental Panel on Climate Change
ISDS	**:**	Inter- Seasonal Dry spell
ISFM	**:**	Integrated Soil Fertility Management
KALRO	**:**	Kenya Agricultural and Livestock Research Organization
KCIDP	**:**	Kitui County Integrated Development Plan
$KMnO_4$-C	**:**	Permanganate Oxidizable Carbon
KNBS	**:**	Kenya National Bureau of Statistics
LFOC	**:**	Light Fraction Organic Carbon
LSD	**:**	Least Significant Difference
MAM	**:**	March, April and May
MBC	**:**	Microbial Biomass Carbon
MWD	**:**	Mean Weight Diameter
N	**:**	Nitrogen
NDMA	**:**	National Drought Management Authority
NGO	**:**	Non-Governmental Organization
NRC	**:**	National Research Council
OND	**:**	October, November and December
P	**:**	Phosphorous
POC	**:**	Particulate Organic Carbon
RCBD	**:**	Randomized Complete Block Design
SOC	**:**	Soil Organic Carbon

SOM : Soil Organic Matter

SSA : Sub-Sahara Africa

TOC : Total Organic Carbon

DEFINITION OF TERMS

Conventional planting	**:**	From this context, its traditional farming practice on flat land without use of *Zai* pits.
Integrated soil fertility Management	**:**	A set of soil fertility management practices related to the use of fertilizer, organic inputs, and other amendments combined with the knowledge on how to adapt these practices to local conditions with the aim of maximizing the agronomic use efficiency of the applied nutrients and improving crop productivity (Vanlauwe *et al.*, 2010).
Soil aggregate stability	**:**	Ability of soil aggregates to resist disintegration when disruptive forces associated with tillage and water or wind erosion are applied.
Soil amendment	**:**	Addition of any materials to soil in order to improve its physical and chemical properties.
***Zai* pit**	**:**	basins, troughs or holes of 20-30 cm in length and width and about 10-30 cm in depth used for agricultural activities (Sawadogo, 2011).

ABSTRACT

Low crop productivity, high evapotranspiration and low, erratic and unreliable rainfall among farms of sub-Saharan Africa (SSA) have necessitated a search for more sustainable production practices with higher efficiency in resource utilization. To ease soil fertility deterioration and reduce runoff and water related stress, integrated soil fertility management (ISFM) coupled with water harvesting technologies such as *Zai* pit, are alternative options with positive impact on agricultural productivity. The main objective of this study was to assess the effects of *Zai* pits combined with selected ISFM amendment options on Gadam sorghum (*Sorghum bicolor)* yields and selected soil properties in Kitui County. The specific objectives were to: 1) assess the effects of *Zai* pit system combined with ISFM technologies on soil chemical properties and Gadam sorghum yields in Kitui County, 2) evaluate the impact of *Zai* pit system combined with ISFM technologies on soil aggregate stability and moisture content in Kitui County, 3) determine the effects of *Zai* pit system in combination with ISFM technologies on soil organic carbon and its labile organic carbon fractions in Kitui County, 4) evaluate the effects of *Zai* pit system in combination with ISFM technologies on soil microbial biomass (Carbon and Nitrogen) in Kitui County. The experiment was set up in a randomized complete block design (RCBD) with eight treatments replicated three times. Each experimental plot measured 6 by 4.5 m. The field experiment ran for four consecutive cropping seasons; short rains of 2018 (SR2018), long rains of 2019 (LR2019), short rains of 2019 (SR2019) and the long rains of 2020 (LR2020). The treatments comprised of two systems, either *Zai* pit or convention system (no *Zai* pits), both with four levels of fertilization (no input - control), sole cattle manure, sole mineral fertilizer and both cattle manure and mineral fertilizer). Soil sampling was done at a soil depth of 0-15cm at the start, during and at the end of the experiment for laboratory analyses of various soil parameters. Data was subjected to Analysis of Variance (ANOVA) and further means separated using the Least Significance Difference (LSD) at $p \leq 0.05$. Pairwise comparison of selected soil parameters differences between the start and the end of the experiment were analyzed using t-test at $p \leq 0.05$. The results indicated that there was a significant difference ($p = 0.01$, $p = 0.02$, $p = 0.01$ and $p = 0.02$) in soil pH, EC, % nitrogen and extractable phosphorous, respectively, between treatments at the end of the experiment. Generally, treatments under *Zai* system recorded significantly ($p \leq 0.05$) higher sorghum grain and stover yields during the SR2018, SR2019 and LR2019 seasons as compared to similar treatments under the conventional system. Significantly ($p \leq 0.05$) highest grain yields were recorded under *Zai* system with sole manure and those with manure combined with mineral fertilizers. Generally, aggregate stability of soil particles was significantly higher ($p \leq 0.05$) in *Zai* treatments as opposed to alike treatments in the conventional system. *Zai* pit with manure combined with inorganic fertilizer recorded the highest significant ($p \leq 0.05$) mean weight diameter of 2.06 mm followed by *Zai* with sole manure (2.01 mm) and this were 35% and 25% higher than the mean weight diameter recorded in similar treatments under conventional system. The determination of Soil moisture content, expressed as volumetric water content, was done at different days (18, 32, 46, 60, 74, 88, 102 and 116) after sowing during the four study seasons. Generally, treatments under *Zai* pit system recorded significantly ($p \leq 0.05$) higher volumetric water content values as opposed to values recorded in similar treatments under conventional system across different days in all the four seasons. Higher values were recorded in treatments with absolute manure and those with organic manure combined with chemical fertilizer under both systems. Significantly ($p\leq0.05$) higher concentrations of total organic carbon, its labile fractions (POC, LFOC, DOC and $KMnO_4$-C) and microbial biomass (carbon and nitrogen) were recorded in treatments under *Zai* pit technology as compared to the conventional system and in treatments amended with organic manure, either solely or combined with mineral fertilizer as opposed to mineral fertilizer amended treatments and the unfertilized control. Based on the findings, *Zai* pit technology coupled with integrated organic and inorganic inputs could be a major agricultural intervention for improving soil fertility and enhancing crop productivity in arid and semiarid areas, and therefore, there is need for agricultural policy makers to develop and implement appropriate agricultural guidelines for extension service providers and smallholder farmers on the effectiveness and efficiency of the technologies in the study.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Introduction

Many of the sub-Saharan African soils are degraded, fragile, and have low fertility by nature. The uptake of major plant nutrients frequently exceeds replenishment in the majority of African nations (Vanlauwe *et al.*, 2015). In addition, the organic matter content of soils has diminished and the pressure from an expanding population has made conventional fertility restoration techniques less effective. As a result, there has been reduced efficiency of mineral fertilizers and vulnerability to drought has intensified as a result of the soil's reduced capacity to retain moisture (Vanlauwe *et al.,* 2015; Altieri & Koohafkan, 2008). This chapter presents background of the study, statement of the problem, objectives, research questions, significance and scope of the study.

1.2 Background to the study

Low nutrient and inadequate water supply are the major drawbacks that limit crop productivity around the world (Hengsdijk & Langeveld, 2009). Decline in crop productivity has also been linked to soil moisture stress (Rockström & Karlberg, 2010). Insufficient water is a major constraint to agricultural development in many areas of the world (Aroka, 2010). In most tropical regions of the world where many countries are less developed, water scarcity and the resultant food insecurity are of a particular concern (Aroka, 2010).

FAO (2010) estimated that rain-fed agriculture contributes to about 60% of the world crop production. For most countries in Sub-Saharan Africa (SSA), agriculture is a significant sector of their economy with close to 70% of the total population from the region living in rural areas and largely counting on small scale subsistence agriculture for their livelihood security (Rockstrom, 2000). In most countries in Sub Saharan Africa, irrigation typically occurs on less than 5% of the total cultivated land (Peacock *et al.,* 2004). The uncertainty and risk for current farm level production associated with variability of rainfall amount and distribution within and between the seasons has lowered the potential influence of innovations aimed at improving farm productivity (Biazin *et al.,* 2012). This is because the uncertainty discourages the decision to invest in improved farming practices by the farming communities and the wide range of stakeholders in agriculture (Cooper & Coe, 2011). The uncertainty of rainfall amounts and distribution, and the high evapotranspiration makes crop production a risky enterprise in semi-arid areas, as a result of agricultural drought and intra-seasonal dry spells (ISDS) leading to reduced yield in rain-fed agriculture (Kahinda *et al.,* 2007).

Most of the agriculture in Sub-Saharan Africa is rain-fed. Rain-fed agriculture in Africa, which is characterized by droughts in most parts (Rockström & Karlberg, 2010) has threatened food demand projected by 2050 (Grafton *et al.,* 2015). With such projections, rain-fed agriculture is one of the most vulnerable sectors to climate variability as Intergovernmental Panel on Climate Change (IPCC) reports that agriculture production will be severely affected by climate change (IPCC, 2007). Despite this, it is imperative to recognize that the situations in many African countries are manageable. The global crop yield growth average of the major cereals in the world varies between 0.9 % and 1.6 % per year and the increase rates have fallen in the past two decades (Grafton *et al.,* 2015). There is need to produce more to sustainably meet the food needs of the ever-growing human population. Thus, this necessitates the need to develop new strategies for agricultural production in sub-Saharan Africa. These situations suggest that the challenges of limited yields in rain-fed farming systems in SSA might be overcome with soil water conservation techniques combined with fertility management technologies (Rockström & Karlberg, 2010). These combinations generate systems that further increase water efficiency and yields in smallholder farms (Winterbottom *et al.,* 2013).

Zai pit is a form of ancient dryland farming technique that was first initiated in Burkina Faso although some literature points it to Dogon in Northern Mali (Danjuma & Mohammed, 2015). It involves the utilization of basins or holes of 20cm-120cm and about 10cm-60cm in depth for agricultural activities (Sawadogo, 2011). It improves water status in the soil and increases decomposition and nutrient release (Zougmoré *et al.,* 2014). Their utilization has been found to minimize the effects of droughts since they ensure soil maintenance, soil erosion control and water preservation.

Zai pits are capable of collecting up to 25% or more of run-off coming from five times its area (Malesu *et al.,* 2006) and allowing crops to do well in areas with high risk of crop failure as a result of harsh climatic conditions (Critchley & Gowing, 2013). Water stored in the *Zai* pits delay the onset and occurrence of severe water stress thereby buffering the crop against damage caused by water deficits during dry periods (Nyamadzawo *et al.,* 2013). *Zai* pits increase the amount of water stored in the soil profile by trapping or holding rainwater where it falls (Mutunga, 2001). Besides enhancing water storage, *Zai* pits increases water infiltration and reduces run-off for plant uptake during the dry periods (Drechsel *et al.,* 1999). The pits play a key role in water harvesting.

Zai pit system is one of the most successful interventions that ensure reduction in runoff and evaporation, improved precipitation capture and improved agricultural productivity (Evett & Tolk, 2009). Since most lands under cultivation are characterized by compaction, reduced permeability, limited plant root development and inadequate aeration (Zougmoré *et al.,* 2014), pit digging facilitates more water infiltration and thus runoff water is harvested due to the earthen bund formed down slope of the pits (Kaboré & Reij, 2004). Despite this, *Zai* pits have been found to be efficient when combined with other soil moisture conservation methods and organic and inorganic soil inputs (Burpee *et al.,* 2015).

The application of soil fertility management inputs enhances soil nutrient availability and improves nutrient uptake by crops from soil reserves (Kar *et al.,* 2013). Besides supplying macronutrients and micronutrients to the soil (Tirol-Padre *et al.,* 2007; Negassa *et al.,* 2001) cattle manure has been found to improve the physical and chemical properties of soil (Tirol-Padre *et al.,* 2007). Cattle manure application increases soil pH (Wildemeersch *et al.,* 2015; Mucheru-Muna *et al.,* 2014, 2007; Mutegi *et al.,* 2012; Mugwe *et al.,* 2009), electrical conductivity (Ozlu & Kumar, 2018; Zhu *et al.,* 2018; Cai *et al.,* 2015; Zhao *et al.,* 2014) and Soil organic matter concentration (Omenda *et al.,* 2021; Xin *et al.,* 2016;

Zhou *et al.,* 2016; Mucheru-Muna *et al.,* 2007; Bayu *et al.*, 2005) as compared to inorganic fertilizer.

Livestock manure has been known to provide higher phosphorous levels to soil compared to other organic inputs (Muui *et al.,* 2013; Opala *et al.,* 2012; Mucheru-Muna *et al.*, 2007; Tirol-Padre *et al.,* 2007). By raising soil organic matter, it increases cation exchange capacity and improves soil physical properties (Bationo, *et al.,* 2007). The use of cattle manure generally increases sorghum yields (Kimaru-Muchai *et al.,* 2021), wheat grain and straw yield (Coventry *et al.*, 2011) and maize yields (Omenda *et al.,* 2021) by providing nutrients and increasing the soil's capacity to hold those nutrients. Increased yields due to use of animal manure has also been reported in other studies in central Kenya (Kimani *et al.,* 2004; Lekasi *et al.,* 2003).

Studies have shown that Kenya is one of the most vulnerable countries to climate variability and changes due to its low adaptive capacity and over-dependence on climate sensitive sectors such as rain-fed agriculture (FAO, 2011; Herrero *et al.*, 2010; Kurukulasuriya *et al.,* 2006). Like many other countries in SSA, Kenya has had significant drought events; for example, the 2004-2006 drought that affected food availability for 2.5 million people (Rarieya & Fortun, 2010). This can be attributed to low soil fertility and moisture deficits inhibiting crop production in the arid and semi-arid areas (Gichangi *et al.*, 2006). Use of suitable water and soil management technologies such as *Zai* pit (Evett & Tolk, 2009) increases water use efficiency and bridge intra-seasonal dry spells (Dile *et al.*, 2013).

Positive impacts of *Zai* pit combined with integrated soil fertility management (ISFM) inputs on agricultural productions of different crops have been recorded in other studies (Sawadogo, 2011; Kaboré & Reij, 2004). *Zai* pits combined with cattle manure has been known to promote soil fertility (Sawadogo, 2011; Fatondji *et al.,* 2006) and increase organic matter content (Barry *et al.,* 2009) in soil as compared to use of mineral fertilizer. Other studies have recorded increased yields in *Zea mays* (maize) (Recha *et al.*, 2014), *Pennisetum glaucum* (pearl millet) (Fatondji, 2002) and *Sorghum bicolor* (Sawadogo, 2011).

Most farmers in Eastern Kenya are entirely depended on rain-fed agriculture as a source of livelihood sustenance and to meet their daily food demands. The study area, which is located in Eastern Kenya, is characterized by low, erratic and unreliable rainfall, high temperatures and thus high evaporation rates. These, coupled with low soil fertility has resulted to low, insufficient crop yields among farmers thus resulting to enhanced food insecurity. This necessitates the need of research aimed at improving crop production for food security in the area. Majority of studies on the *Zai* system have been conducted in the Sahelian region of West Africa with limited research being conducted in the Eastern Africa ASALs, and especially in Eastern Kenya. In Kenya, limited research have been done in various parts, including: Tharaka nithi, Machakos, Makueni and Kitui, to assess the impact of *Zai* system on crop yield (Getare *et al.,* 2021; Kimaru-Muchai *et al.,* 2021; Oduor *et al.,* 2021). Other research related to *Zai* pit system have been conducted to assess communication (Njenga *et al.,* 2021) and socio-economic (Muriu-Ng'ang'a *et al.,* 2017; Mutuku *et al.,* 2017) factors influencing its adoption and utilization.

While the majority of past studies focused on the impact of *Zai* on crop yields and the factors influencing their adoption, there is still scanty information on its potential to enhance soil characteristics and crop productivity when combined with integrated soil fertility management practices. In the ASALs, water (soil moisture), nitrogen and phosphorus significantly limit crop productivity (Okalebo *et al.,* 2007; Keating *et al.,*1990). It is therefore necessary that such studies in ASALs should aim at addressing both moisture and fertility deficiencies. Hence the focus of this study was to assess the influence of *Zai* pit as a technique that conserves moisture combined with integrated nutrient management strategies for fertility restoration in the ASALs using *Sorghum bicolor* (Gadam variety) as a test crop.

1.3 Statement of the problem

Climate change has been found to be one of the major challenges facing agriculture (Rosegrant *et al.,* 2002) especially in arid and semi-arid areas (ASALs) of Eastern Kenya, which are naturally characterized by high temperatures and low, erratic rainfall (Jaetzold *et al.,* 2007). Furthermore, inherent and induced deficiencies of major nutrients (Phosphorus, Nitrogen and Potassium) as well as low soil moisture (Sanchez, 1997) has resulted to low agricultural productivity thus rendering the region food insecure year after year. The low, unreliable and erratic rainfall received in Eastern Kenya has resulted to low soil moisture and low yields. The situation is aggravated by an over reliance on rain fed agriculture (Fatondji, 2002) which exposes farmers to extreme weather conditions commonly experienced in the region.

Diminishing soil fertility continues to be a constraint to crop production in Eastern Kenya (Kitui included) due to lack of or inefficient soil fertility management practices and nutrient utilization without adequate replenishing. In addition, most farmers in this region are small scale farmers and lack adequate resources to maintain optimum farm nutrient requirements, causing continued soil fertility decline (Hartemink, 2006) and thus decline in food production. This situation is compounded by farmers giving prominence to maize, a crop with high nutrient requirements at the expense of indigenous crops (such as sorghum) that are better adapted to local conditions (NRC, 1996).

Limited information exists on the impact of *Zai* pits system combined with ISFM options on crop yields. Despite various studies in Africa providing useful insight on impact of *Zai* pits in production of various cereal crops (Kaboré & Reij, 2004; Fatondji, 2002), limited research has been conducted to evaluate their impacts, especially when combined with ISFM amendment options on specific soil properties which are important in crop productivity. Sorghum production has widely been promoted in the ASALs due to its tolerance to drought, ability to thrive well in a range of soils and low input requirements, compared with most staple cereals like maize.

To ascertain effectiveness of *Zai* pits in combination with different soil fertility management techniques on crop production, there is need to evaluate their effects on specific soil parameters such as soil organic carbon and its fractions, soil moisture content, stability of soil aggregates as well as soil microbial biomass which this study sought to undertake.

1.4 Objectives of the study

1.4.1 General objective

To assess the contribution of *Zai* pits combined with selected ISFM amendment options on Gadam sorghum yields and selected soil properties in Kitui County

1.4.2 Specific objectives

i. To assess the effects of *Zai* pit system combined with ISFM technologies on soil chemical properties in relation to Gadam Sorghum yields in Kabati, Kitui County.

ii. To evaluate the impact of *Zai* pit system combined with ISFM technologies on soil physical characteristics in Kabati, Kitui County.

iii. To determine the effects of *Zai* pit system in combination with ISFM technologies on soil organic carbon in Kabati, Kitui County.

iv. To evaluate the effects of *Zai* pit system in combination with ISFM technologies on soil microbial biomass in Kabati, Kitui County.

1.5 Research hypotheses

The study was guided by the following hypotheses:

i. H_0- *Zai* pit system in combination with ISFM technologies has no significant effect on the soil chemical properties in relation to Gadam Sorghum yields in Kabati, Kitui County.

   H_i - *Zai* pit system in combination with ISFM technologies has significant effects on the soil chemical properties in relation to Gadam Sorghum yields in Kabati, Kitui County.

ii. H_0- *Zai* pit system combined with ISFM technologies has no significant influence on soil physical characteristics in Kabati, Kitui County.

    H_i- *Zai* pit system combined with ISFM technologies significantly influences soil physical characteristics in Kabati, Kitui County.

iii. H_0- *Zai* pit system in combination with ISFM technologies does not significantly affect soil organic carbon in Kabati, Kitui County.

    H_i- *Zai* pit system in combination with ISFM technologies significantly affects soil organic carbon in Kabati, Kitui County.

iv. H_0- *Zai* pit system combined with ISFM technologies has no significant impact on soil microbial biomass in Kabati, Kitui County.

    H_i- *Zai* pit system combined with ISFM technologies has significant impacts on soil microbial biomass in Kabati, Kitui County.

1.6 Significance of study

The data gathered in this study will be useful in providing feedback to farmers and extension officers on *Zai* pits designing and implementation. The results of this study will be instrumental in identifying the most appropriate cultivation system coupled with the most effective soil fertility amendments for the soils in the study area and other areas with similar soil characteristics. The results will be useful to extension service providers in planning, designing and evaluating efficient and effective agricultural policies, programs and projects at local, regional and national scales for the farmers in the sub-humid and semi-arid regions in the SSA. The results will also give insight to farmers on the use of *Zai* pit as a technology for soil moisture retention. The findings will also raise awareness to farmers in these regions with regards to choosing appropriate technologies for soil fertility improvement and water harvesting techniques.

1.7 Scope of the study

The study was carried out at Kabati area, located in the Kitui West Sub County in Kitui County. The region is classified as a semi-arid area and was therefore purposefully selected to represent Kenya’s ASALs. The study focussed on assessing the effects of *Zai* Pits combined with selected ISFM technologies on Gadam sorghum yield and selected soil properties through a field experiment that was set up in the beginning of the 2018 short rains season and ran for four consecutive seasons through to the end of the 2020 long rains season. ISFM is defined as a set of soil fertility management practices that include the use of fertilizer, organic inputs, improved germplasm combined with other sustainable agricultural practices like mulching and intercropping. This study was however limited to the use of organic and inorganic fertilizer component of ISFM. The operations, activities and data collection were strictly confined within the boundaries set by the study objectives.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

This section discusses the empirical literature concerning *Zai* pit system and integrated soil fertility management (ISFM) technology and their effects on crop yield and soil properties of interest to this study. Lastly, it gives summary of the literature gaps identified and the conceptual framework.

2.2 General overview

Most dryland parts of Kenya are characterized by unreliable rainfall distribution and declining soil fertility that are unsuitable for sustainable rain-fed agriculture in arid and semi-arid lands (Miriti, 2011). Approximately, 83% of Kenya's land surface is classified as arid and semi-arid lands (ASALs). This means that they experience low and erratic rainfall (100-900 mm per annum) which is unsustainable for agricultural production (Njoka *et al.,* 2016). Agricultural production is affected by the high variability of rainfall onset, distribution and frequent droughts which usually occur during the growing season, often resulting in depressed yields and persistent crop failures (Miriti *et al.,* 2012; Keating *et al.*, 1990).

The Kenyan ASALs are experiencing low crop production due to a combination of biophysical factors such as low rainfall, surface sealing, unavailability of high-quality manure, declining soil fertility due to continuous cultivation and crust formation that reduces soil water availability to crops (Gitau, 2004; Gicheru, 2002). This has aggravated the food insecurity issue since majority of farmers in ASALs of Kenya depend on crop production and livestock keeping for livelihood sustenance (Gicheru, 2002). With constraints such as unreliable rainfall and high evapotranspiration rates which limit crop production, there is limited food availability posing food insecurity (Altieri & Koohafkan, 2008). To rescue situations of crop failures arising from rainfall variability and unpredictability, most farmers have opted to adopt water harvesting and soil management techniques so as to ensure soil conservation and increase the rates of water infiltration as well as replenish soil fertility (Biamah, 2005). Soil nutrient deficiency and water scarcity in semi-arid farming systems are limiting factors to crop growth (Fox & Rockström, 2003; Breman *et al.,* 2001).

Most farmers rely on stable crops such as millet and sorghum as a result of variability in rainfall and declining soil fertility in ASALs of Kenya (KNBS, 2005). Research has shown that lack of soil moisture is also one of the major constraints to land productivity in ASALs of Kenya (Itabari *et al.,* 2003). Much research carried out over the years has revealed that rainwater harvesting in combination with soil fertility amendment options has significantly increased crop production (Gichangi *et al.,* 2007; Itabari & Wamuongo, 2003).

2.3 Sorghum production

Sorghum bicolor is one of the most important cereal crop in ASALs of the world yet so under-utilized. The crop has a remarkable tolerance for drought and has the ability to survive periods of water logging and floods (Takuji & Baltazar, 2009). Sorghum is distinguished by a waxy bloom that prevents water loss from the leaves, extensive root system for moisture uptake, the capacity to halt growth during dry spells and resume it when the stress is alleviated, and C4 photosynthesis (Paterson, 2008; Wortmann *et al.,* 2009). Sorghum crops can therefore withstand the extreme environmental conditions of ASALs (Muui *et al.,* 2013; Ritter *et al.,* 2007). The crop has been found to do well in regions between 500 to 1700 meters above sea level and receiving a seasonal rainfall of 300mm or more.

Sorghum is a staple food for millions of people. The grain is used to make traditional foods including ugali, pilau, and both fermented and non-fermented porridge (MoA, 2010). Due to the it's high levels of iron (>70 ppm) and zinc (>50 ppm), it has the ability to reduce micronutrient deficiency. The nutritional value of sorghum is as follows: Protein- 8 %, Carbohydrates- 76.64 %, Fat- 3.34 %, Sugar- 1.9 %, Fiber- 6.60 %, Zinc- 1.63 %, Sodium- 3 %, Iron- 3 % (Safi-Organics, 2023). Sorghum is also a rich source of fiber and antioxidants. The baking industry uses sorghum to manufacture unleavened and leavened bread. It is also utilized as animal feed and a raw material in industry (Dicko *et al.,* 2006; Agrama & Tuinstra, 2003) for the production of wax, starch, syrup, alcohol, dextrose agar, edible oils, and gluten feed (Muui *et al.,* 2013; Dicko *et al.,* 2006). Sorghum is widely used as a substitute for barley in the brewery industry. Despite its wide range of uses, farmers do not produce enough sorghum grain to meet the market demand.

Sorghum has been neglected and is regarded as a low-potential crop yet it remains an untapped and unexplored natural resource. With more than 42,000 accessions, it possesses one of the largest collections of grain germplasm (Huang, 2004; Dahlberg *et al.,* 2002). A vast and diversified germplasm offers excellent chances for sustainable crop production, diversity in diet and the provision of deficient micronutrients while at the same time offering additional income to farmers (Muui *et al.,* 2013; Huang, 2004). However, small-scale farmers' ability to grow sorghum in ASALs is limited by a shortage of inputs, seeds, vulnerability to diseases and low yields realized.

Sorghum bicolor is an indigenous crop to Africa, and though commercial needs and uses may change over time, sorghum remains a basic staple food for many rural communities (Kangama, 2017). This grain is ranked as the fifth most important cereal crop grown in the world (U.S. Grain Council, 2005). It is also the second most important cereal food after maize for the millions of people living in the ASALs of Africa (Taylor, 2003).

In Kenya, sorghum is an important food crop in the dry land areas of Eastern and Nyanza provinces (Kangama, 2017). It is produced in Kenya's Eastern (1385 m ASL, 76 mm month-1), Nyanza (1190 m ASL, 130 mm month-1), and Coast Provinces (185 m ASL, 87 mm month-1), which regions that are frequently subject to drought. (Muui *et al.,* 2013).

The production of this cereal has widely been promoted in the ASALs due to its tolerance to drought, ability to thrive well in a range of soils and low input requirements, compared with most staple cereals like maize (Mwadalu & Mwangi, 2013). Sorghum, an indigenous Kenyan crop, has the potential to provide food security and serve as a viable substitute in eastern Kenya, where maize crop failure is prevalent (Jaetzold *et al.,* 2007; MoA, 2003). Sorghum promotion has mainly been done as a strategy to enable the government meet household food security needs and increase rural income among the smallholder farmers in the semi-arid areas of Kenya (Ochieng *et al.,* 2011). In recent years, sorghum has been on demand within the brewing industry as the best alternative to barley for larger scale beer brewing (Taylor, 2003). In terms of utilization, Sorghum is closely related to maize and is therefore a viable substitute crop to maize in ASALs (Swigoňová *et al.,* 2004; Kellogg, 2001).

Gadam sorghum variety was introduced by Kenya Agricultural and Livestock Research Organization (KALRO) formerly, Kenya Agricultural Research Institute (KARI) to semiarid Eastern Kenya in 2009 as a way for farmers to reduce food insecurity and better their lives from the sales of its produce (Esipisu, 2011). Gadam has high yields, maturing early and is drought resistant (Esipisu, 2011). The grain of Gadam sorghum is low in protein and high in starch, which makes it suitable for malting (Miano *et al.,* 2010). Despite the efforts put in promotion of Gadam sorghum, there has been variability in production from the expected potential yields and the actual yields (Chepng'etich *et al.,* 2015). The expected potential yield for the Gadam sorghum variety is 4-5 t ha^{-1} (Karanja *et al.,* 2006). Unfortunately, farmers have only recorded production of up to 1.2 t ha^{-1} (Karanja *et al.,* 2009). The low current production is due to the erratic rainfall and low use of inputs to boost soil fertility among other factors (Muui *et al.,* 2013; Miano *et al.,* 2010). It is for this reason that the study opted to use Gadam sorghum as its test crop, and assess its potential yields using *Zai* pit as a soil water conservation technique with different inputs for soil fertility amendments.

2.4 *Zai* pit system

Zai pit is a form of ancient dryland farming technique that was first initiated in Burkina Faso although some literature points it to Dogon in Northern Mali (Danjuma & Mohammed, 2015). It involves the utilization of basins or holes of 20 cm-30 cm and about 10 cm-15 cm in depth for agricultural activities (Sawadogo, 2011). Their utilization has been found to minimize the effects of droughts since they ensure soil stability, soil erosion control and water preservation. Farmers in various parts of the world have used this technique to combat land degradation and to restore soil fertility (Fatondji, 2002). Fatondji (2002) found that use of *Zai* pits had a good potential to increase nutrient use efficiency, agronomic efficiency, and pearl millet grain yield in Niger. In Burkina, Zougmoré *et al.* (2014) reported that *Zai* pit reduces runoff by increasing infiltration through creating and enhancing depressional water storage and reducing erosion.

A study by Sawadogo (2011) reported increased yields variations from 300 to 400 kg ha^{-1} by the *Zai* system in degraded land. Oduor *et al.* (2021) reported that *Zai* pit technique with manure increased crop yield. Sawadogo (2011) reported substantial grain yield increases where he reported sorghum yields increase in farmer's fields from 319-642 kg ha^{-1} without *Zai* pit system to 975-1600 kg/ha with *Zai* pit system. The use of *Zai* pit system has also been reported in South Africa (Magombeyi & Taigbenu, 2008), Zambia (Thierfelder & Wall, 2009; Haggblade & Tembo, 2003), Ethiopia (Amede *et al.,* 2011), Niger (Fatondji *et al.,* 2009) and Zimbabwe (Gumbo *et al.,* 2012).

In Kenya, *Zai* pits technology has been recommended as a water harvesting technique for the production of maize in the coastal region (Saha *et al.,* 2007) and in the eastern region (Recha *et al.,* 2014). Tumbukiza is a variation of the *Zai* pit technique that has been widely utilized by farmers in western Kenya as a method of napier grass production (Orodho, 2007). Variations of *Zai* pits have been used in various parts of Kenya including the katumani pit and 'five by nine' pit in Tharaka nithi, Murang'a and Machakos Counties (Malesu *et al.,* 2006).

2.4.1 Effects of *Zai* pit system on soil moisture

Water is an important factor in plant growth. *In-situ* soil moisture conservation entails capturing rainwater and retaining it in the soil for in-situ plant utilization for growth and increase in grain and biomass yield (Itabari & Wamuongo, 2003). Water harvesting and storage is vital to ensure water availability for plant growth especially in the arid and semi-arid areas. *Zai* have been found to be capable of collecting up to 25% or more of a run-off coming from 5 times its area (Malesu *et al.*, 2006). *Zai* pits are known to allow crops do well in areas with high risk of crop failure as a result of harsh climatic conditions (Critchley & Gowing, 2013). Water stored in the *Zai* delay the onset and occurrence of severe water stress thereby buffering the crop against damage caused by water deficits during dry periods (Nyamadzawo *et al.*, 2013). *Zai* pits increase the amount of water stored in the soil profile by trapping or holding rainwater (Mutunga, 2001). Besides enhancing water storage, *Zai* pits increases water infiltration and reduces run-off for plant uptake during the dry periods (Danjuma & Mohammed, 2015). The pits play a key water harvesting role. Instead of being lost to runoff, rainfall water is trapped in the *Zai* pits close to crop roots. *Zai* pits are especially relevant to areas receiving 300- 800 mm annual rainfall (Mwangi, 2020).

Despite their importance in increasing soil moisture in low rainfall areas, studies have also revealed the significance of using *Zai* pits in high rainfall areas with steep slopes. Such areas receive high rainfall but due to steep slopes, most of the water end up as run-off and results to massive soil erosion. A study by Amede *et al.* (2011) showed that *Zai* pits were effective in a highland area of Ethiopia that receives in excess of 1300 mm annual rainfall and where water infiltration into the soil is limited by losses of rainwater to runoff, a lack of organic matter, and hardpans. In their study Amede *et al.* (2011) found out that Crop water productivity of potato and beans was 300–700% higher with *Zai* pits than with control plots. In summary, the *Zai* system allows farmers to concentrate both fertility and moisture close to crop roots and, in so doing, addresses some of the major challenges to crop production in Sub-Saharan Africa (Mwangi, 2020).

2.5 Integrated soil fertility management (ISFM) technology

Integrated soil fertility management (ISFM) is a means to increase crop productivity in a profitable and environmentally friendly way (Bationo & Waswa, 2011; Vanlauwe *et al.*, 2010). It aims at offering wide-ranging solutions that are socially acceptable and practical in the management of soils (Misiko, 2007). The ISFM paradigm became crystallized at the turn of the millennium with a new emphasis on improving the use efficiency of inorganic and organic fertilizer combinations while adapting nutrient management strategies to local conditions (Kolawole, 2013; Bationo & Waswa, 2011).

Integrated soil fertility management (ISFM) is a means to increase crop productivity in a profitable and environmentally friendly way (Vanlauwe *et al.,* 2010), and thus eliminating one of the main factors that perpetuates rural poverty and natural resource degradation in sub-Saharan Africa (SSA). Current interest in ISFM results from global demonstration of the benefits of ISFM interventions, such as the combined use of organic manure and mineral fertilizers (Zingore *et al.,* 2008), dual purpose legume – cereal rotations (Sanginga & Woomer, 2009) or micro-dosing of fertilizer and manure for cereals in semi-arid areas (Tabo *et al.,* 2007). Integrated soil fertility management is also aligned to the principles of Sustainable Intensification (Vanlauwe *et al.,* 2014; Pretty *et al.,* 2011), one of the paradigms guiding initiatives to increase the productivity of smallholder farming systems.

The benefits of ISFM technologies in enhancing fertilizer use efficiency and improving maize productivity are widely acknowledged in literature (Lambrecht *et al.,* 2014; Mucheru-Muna *et al.,* 2014; Fairhurst, 2012; Mugwe *et al.,* 2009; Marenya & Barrett, 2007). According to Kamau *et al.* (2014), ISFM has the potential to reduce the need for chemical fertilizers owing to its ability to raise the efficiency of the applied nutrients. The adoption of ISFM technologies can also lead to economic benefits if gains in profits due to improved input productivity exceed the cost of adoption (Kamau *et al.,* 2014). The use of inorganic and organic fertilizers such as compost manure, green manures, crop residues and legume integration in farming systems is one component of ISFM (Mhango *et al.,* 2013).

These organic fertilizers improve soil organic matter, nutrient and water retention in soils. ISFM technologies can enhance fertilizer use efficiency and thereby improve productivity (Fairhurst, 2012). Practices in ISFM technologies such as integration of legumes and incorporation of crop residues improve soil organic matter (Mucheru-Muna *et al.,* 2010).

Snapp *et al.* (2014) reported that rotating maize with a legume crop is another factor that consistently influences maize yield response to nitrogen. Use of ISFM technologies have led to increase in crop yields in many parts of SSA. Kaboré and Reij (2004) indicated that an additional dose of inorganic fertilizer, in combination with the *Zai* pits and manure, increased yields by 640 kg ha^{-1} compared to the control treatment in Mali.

2.6 Effects of *Zai* pit system combined with ISFM technology on crop yield

The results of a study conducted by Fatondji *et al.* (2006) in Niger to examine the effect of *Zai* and organic amendments on millet grain yield reported higher yields in *Zai* plots as compared to the conventional ones, and 68 times more yields in *Zai* plots with manure amendments. In Kitui, the results of a study by Getare *et al.* (2021) revealed that all treatments under *Zai* system recorded significantly higher sorghum grain and stover yields compared to all similar treatments under conventional planting, with the highest significant influence being recorded in *Zai* with combined manure and mineral fertilizer treatment. Similarly, in Tharaka Nithi County, Kenya, Kimaru-Muchai *et al.* (2021) reported significantly higher sorghum grain and stover yields in treatments under *Zai* as opposed to similar treatments under conventional systems, with highest yields being recorded under *Zai* with organic amendments either solely or when combined with chemical fertilizer.

Kaboré & Reij (2004) discovered that *Zai* boosted sorghum yields by 310kg/ha compared to the treatments without *Zai* pits. Average yields in *Zai* pits in Niger's Illela area were 310% higher than untreated fields (Kaboré & Reij, 2004). *Zai* pits technology was found to have yielded much better dry matter yields than the traditional method in Western Kenya (Muyekho *et al.,* 2000). Bationo *et al.* (2007) reported that using *Zai* alone did not boost yields as much as using *Zai* in combination with manure and fertilizer in West Africa. In Niger, manure application with *Zai* increased grain yields by 2 to 69 times as opposed to *Zai* with no treatment (Fatondji *et al.,* 2009).

In the highlands of Ethiopia, Amede *et al.* (2011) demonstrated the effectiveness of *Zai* pits by reporting a 500 percent to 2000 percent and up to 250 percent increase in potato and bean yields, respectively, when *Zai* pits were used in conjunction with nitrogen inputs compared to the control. Similarly, Sawadogo (2011) reported 100% increased crop yields on farms which employed the use of *Zai* pit technology as compared to the 63–74% increase on farms utilizing rock bunds in the study villages. Similar findings were reported by Zougmoré *et al.* (2004) who found that *Zai* had significantly influenced yields, especially when combined manure and chemical fertilizers are used.

Even in the absence of *Zai* pits, several studies have demonstrated the positive influence of integrated soil fertility management options on crop yield. Mucheru-Muna *et al.* (2007) reported that treatments with organic (tithonia) amendments, with or without half recommended rate of mineral fertilizer, gave the highest maize grain yield compared to sole nitrogen treatments while the control treatment consistently gave the lowest yield across all the seasons. Similarly, Mucheru-Muna *et al.* (2014) also reported that treatments with sole organics and those with combined organics and mineral fertilizers significantly increased maize grain yield compared with treatments with the recommended rate of sole mineral fertilizer (60 kg N ha^{-1}) and the unfertilized control. Oduor *et al.* (2021) reported better yield performance in treatments under *Zai* system which recorded 30.5% and 27.9% higher yields against 18.2% and 22.5% in conventional plots in Machakos and Naivasha, respectively. Several other previous studies have documented higher crop yields in *Zai* treatments whether solely or when utilized with sole organic inputs or integrated organic and inorganic inputs (Getare *et al.,* 2021; Mwangi, 2020; Njue *et al.,* 2020; Adamtey *et al.*, 2016; Kathuli & Itabari, 2015; Recha *et al.,* 2014; Fatondji *et al.,* 2012; Amede *et al.,* 2011; Sawadogo, 2011 Drechsel *et al.*, 1999).

2.7 Effects of *Zai* pit system combined with ISFM technology on soil aggregate stability

Fertilization is one of the most crucial factors that influence the stability of aggregates and organic carbon (Li *et al.,* 2020). Chemical fertilization reduces physically protected organic carbon by hastening the breakdown of macroaggregates, whereas manure fertilization increases physically safeguarded organic carbon by stimulating the production of microaggregates (Guo *et al.,* 2019). Fertilization has an impact on both the physical protection of organic carbon and soil aggregates and the evolution of its chemical structure. Nciizah & Wakindiki (2012) observed that, compared to the control, addition of manure increased soil aggregate stability (MWD) by 51% and significantly increased the water stable aggregates which have a diameter > 0.5mm, which led to the formation of more stable macro-aggregates. The effects of the applied amendments on aggregate stability, Similarly, Mamedov *et al.* (2014) reported improved soil aggregate stability in all treatments with organic amendments relative to the control.

Zhang *et al.* (2021) reported increased stability of soil aggregates in treatments amended with manure while significantly lowest MWD were recorded in treatments with sole chemical fertilizers. The results of a study by Xie *et al.* (2015) indicated that the combined application of organic manure and fertilizer significantly increased soil aggregate stability compared to the unfertilized control and the sole mineral fertilizer treatment Similarly, Řezáčová *et al.* (2021) reported that the application of organic amendments (compost and digestates) had a significant positive effect on the stability of soil aggregates and which was also accompanied by increased soil fertility, enhanced resistance to decomposition and abundance of soil microbes. Gielnik *et al.* (2019) and Bipfubusa *et al.* (2008) similarly reported increased the stability of soil macroaggregate with addition of organic inputs to soil.

In a study conducted to determine which fertilizer is useful for improving soil fertility and stabilizing soil aggregates, Guo *et al.* (2019) reported significantly higher MWD in treatments amended with farmyard manure at a depth of 0–15cm. Additionally, in a review of literature analysis to examine the effects of organic inputs on soil aggregate stability over time, Abiven *et al.* (2009), reported that most examined literature had indicated improved stability of soil aggregates with the addition of organic inputs either solely or when combined with mineral fertilizer.

Studies have reported enhanced soil aggregate stability after amending soil with organic inputs or organic combined with inorganic fertilizers (Gautam *et al.*, 2021; 2019; Kamran *et al.*, 2021; Zhang *et al.*, 2021; Shao *et al.*, 2019; Are *et al.*, 2018; Mamedov *et al.*, 2014; Nciizah & Wakindiki, 2012; Olatunji *et al.*, 2012; Jiang *et al.*, 2010; Mosavi *et al.*, 2010; Fortun *et al.*, 1989).

Previous works have reported the effect of zero and minimum tillage on the stability of soil aggregates. Using maize as a test crop, Dominy and Haynes (2002) found out that aggregate stability was substantially greater in zero tillage than conventional tillage systems in the 0-5cm soil depth. The results of a meta-analysis performed on numerous studies spread globally by Mondal *et al.* (2020), to evaluate the effect of zero tillage in comparison to conventional tillage on soil physical properties, including the stability of soil aggregates, suggested that zero tillage significantly improved MWD of aggregates at surface and subsurface layers by 19–58%.

Similarly, Brunel-Saldias *et al.* (2016) reported significantly high MWD in soils under treatments with zero tillage compared to conventional tillage. In a study to examine the influence of different combinations of tillage and straw incorporation management on aggregate stability and crop yield, Song *et al.* (2016) reported increased stability of soil macroaggregates in combined zero-tillage and straw incorporation by 36.38% in the 0–15 cm soil layer and 28.93% in the 15–30 cm soil layer.

2.7.1 Soil Organic Carbon (SOC) and Aggregate stability

Soil organic carbon (SOC) is a major attribute of soil fertility because of its importance to soil physical, chemical and biological properties, particularly the stability of soil aggregates for resisting soil erosion (Lehman *et al.,* 2015). Soil organic carbon (SOC) is comprised of various fractions in varying degrees of decomposition, turnover rates and recalcitrance (Huang *et al.,* 2008). The SOC fractions can be classified as labile, semi labile and recalcitrant. These fractions display different rates of microbial and biochemical degradation (Stevenson, 1994). Presence of different SOC fractions in soil reflect key processes of nutrient availability and cycling, soil aggregation and its consequent stability and soil carbon accumulation (Wander, 2004).

Soil aggregation results from the arrangement of primary and or secondary particles, flocculation and cementation (Hyun *et al.,* 2007). It is a factor of great significance not only for increasing soil productivity and sustainability but also for reducing soil erosion (Six *et al.,* 2000), improving nutrient availability and physical properties such as infiltration, aeration, water retention and water use efficiency (Yuan *et al.,* 2012; Hyun *et al.,* 2007). Tisdall and Oades (1982) reported that mineral particles are bound together to micro-aggregates due to persistent binding agents, which in turn, build macro-aggregates due to the transient and temporal organic binding agents like polysaccharides, roots, and fungal hyphae. The large macro-aggregates are more sensitive to management effects on organic matter, hence serving as a better indicator of changes in soil quality. Soil texture, organic and inorganic binding agents generally determine the stability of aggregates, which in turn determine the severity of soil erosion (Gupta *et al.,* 2009).

There exists a close relationship between soil aggregation and SOC accumulation. SOC promotes soil aggregation, whereas aggregates in return store SOC, reducing the rate of its decomposition (Hermawan & Bomke, 1997). The amount of plant residues and the degree of SOM decomposition are vital factors in the formation and stabilization of aggregate structure for SOC sequestration (Kamran *et al.*, 2021). Aggregate stability is significantly correlated with SOC due to the binding action of humic substances and other microbial byproducts (Gautam *et al.,* 2021; Bottinelli *et al.*, 2017). Studies by Zhang *et al.* (2021) and Rasool *et al.* (2008; 2007) have indicated that soil aggregation properties are dependent on SOC concentration through a reciprocal relationship. Losses in SOC are associated with degradation of soil structure (Six *et al.*, 2000).

Bottinelli *et al.* (2017) demonstrated that the breakdown of aggregates caused by cultivation is responsible for the loss of SOC. Soil aggregates protect soil SOC by forming physical barrier between microbes and enzymes and thus reduce their turnover rate

(Pulleman & Marinissen, 2004). The SOC segregation in the soil is governed by the degree of physico-chemical stabilization of organic carbon inside the aggregates (Pulleman & Marinissen, 2004). Since soil aggregation and stability of aggregates is a function of SOC and its fractions, their concentration and stock are important in determining the formation and stabilization of soil aggregates (Bottinelli *et al.*, 2017). Ayuke *et al.* (2011) found out that there was higher percentage of total macro-aggregates (45 g,100 g^{-1} soil) in plots with farmyard manure and mineral fertilizer treatments compared to all other arable treatments. Aggregate stability is a key factor for physical soil fertility and also affects SOM dynamics (He *et al.,* 2018). Resistance of aggregates to physical stresses positively affects seed germination and rooting of crops, water infiltration, and determines the ability of a soil to store SOM through physical protection against rapid decomposition (Zhao *et al.*, 2021; Bottinelli *et al.*, 2017; Song *et al.*, 2016).

Some of the soil properties which influence aggregate stability are cation content, texture, aluminum and iron oxides, clay mineralogy, SOM and soil fauna (Six *et al.*, 2004). Some of these factors (SOM and soil fauna) are affected by agricultural practices such as crop rotation, residue management, tillage and fertilization regimes (Csitári *et al.*, 2021; Gautam *et al.,* 2021; Are *et al.,* 2018). In several conceptual models, the increase of aggregate stability after organic additions to the soil has been related to the decomposition dynamics of the inputs (Abiven *et al.*, 2009). In their study, Ayuke *et al.* (2011) reported that the application of farm yard manure in combination with mineral fertilizer resulted in stable aggregation at 0–15 cm soil depth compared to all other arable treatments. Their results showed that application of manure in combination with fertilizer was the best among the treatments tested in their study for enhanced C and N stabilization with dual benefits of improving soil physical and chemical properties. This emphasizes the importance of ISFM practices for soil rehabilitation in sub-Saharan Africa.

2.8 Effects of *Zai* pit system combined with ISFM technology on soil moisture

Compared to the conventional planting system, the structure of the *Zai* pits, which is comparable to basins, trap run-off and infiltrating water, limits percolation and preserve water within the 0-30 cm soil depth, thus enhancing the moisture available for uptake by plants in farming systems that utilize *Zai* pit technology (Kimaru-Muchai *et al.,* 2021). Moisture trapped in the *Zai* pits helps to delay the onset and incidence of moisture stress, thus protecting the crop from the effects of water shortages during periods of dry-spells (Nyamadzawo *et al.,* 2013).

In a study conducted in Northern Ethiopia, Zelelew *et al.* (2018) reported that the amount of soil moisture content stored in *Zai* plots with manure amendment was significantly higher than the permanent wilting point throughout the growing seasons. Similarly, while reviewing the history of soil and water conservation in Zimbabwe and farmer driven innovations and water harvesting technologies from other regions, Nyamadzawo *et al.* (2013) found out that several modification of planting pits, including *Zai* pit, have been reported to increase soil moisture content as compared to conventional planting practices. Correspondingly, the findings of a review study conducted by Kathuli and Itabari (2015) on the *in-situ* soil water conservation technologies that have been extensively tested and found favorable for enhancing soil moisture for increased land productivity in the ASALs demonstrated that *Zai* pits, among the other reviewed water conservation practices, led to enhanced soil moisture content, which would not be attained in the case of conventional practice. Kathuli and Itabari (2015) also demonstrated that the use of combined organic and inorganic amendments coupled with soil moisture conservation technologies leads to increased soil moisture content and improved water use efficiency by crops planted in the semi-arid areas. *Zai* pits favors infiltration of moisture into the soil compared to conventional system (Fatondji *et al.,* 2006).

Similar results have been reported by other previous studies where higher soil moisture contents were recorded in *Zai* pit treatments as compared to conventional systems (Reij *et al.,* 2009; Mutunga, 2001). Vohland and Barry (2009) reported improved soil water storage in *Zai* treatments compared to conventional treatments. *Zai* pits have been proven to be capable of gathering up to 25% of run-off from 5 times their area (Malesu *et al.,* 2006). In addition to enhancing the water levels retained in the soil profile, *Zai* pits promote water penetration and reduce run-off, thereby making soil moisture available for plant uptake in the occurrence of dry periods (Drechsel *et al.*, 1999).

2.9 Effects of *Zai* pit system combined with ISFM technology on soil total organic carbon and its labile organic fractions

In an experiment conducted to analyze the effects of long-term fertilization with different fertility treatments on soil organic carbon (SOC) and nitrogen contents, Hao *et al.* (2017) reported that treatments with sole manure and those with combined manure and mineral fertilizer significantly increased the soil organic carbon stocks in the soils. Likewise in China, the results of a study by Song *et al.* (2015) revealed that SOC stocks in combined inorganic fertilizers plus farmyard manure treatment was 61% and 50.7% significantly greater than the initial levels and the unfertilized control in the 0-20cm soil layer, respectively. Similar results were reported by Ma *et al.* (2021), who concluded that organic input quality and nitrogen fertilization can interactively increase SOC contents in the soil. Utilization of farmyard manure can result in an increase in lignin and lignin-like compounds, which are important components of the soil's resistant carbon pool (Lima *et al.,* 2009). Manure directly enhances carbon inputs into the soil and also influences crop residues, which potentially sequestrates agricultural soil organic carbon and nutrient release (Cai *et al.,* 2015). Various studies have shown that increases in total organic carbon levels are directly related to the amounts of organic residues added to soils, in fertilizer and manure application (Lemke *et al.,* 2010; Hati *et al.,* 2007; Cai & Qin, 2006).

In India, Anantha *et al.* (2020) reported significantly higher SOC contents with joint application of mineral fertilizer and organics while the little change in SOC contents, compared to the unfertilized controls, were recorded in treatments with sole mineral fertilizer application. According to Ding *et al.* (2012), high SOC concentrations in manure-amended soils suggest that manure addition may be a long-term strategy for improving soil organic carbon stabilization.

Li *et al.* (2018b) reported that treatments which received organic manure had significantly higher total organic carbon concentrations and stocks compared to the those with mineral fertilizer and the unfertilized control treatments. Lin *et al.* (2009) reported that substituting 100% or 50% of mineral fertilizers with organic manure could enhance total organic carbon compared to equivalent mineral fertilizer treatments. According to Li, *et al.* (2018b), regular additions of organic inputs such as manure can raise SOC stocks to a greater level. Li *et al.* (2018c) revealed that after nine years application of organic fertilizers, substantially increased soil organic content while application of chemical fertilizers alone did not affect soil organic levels compared with that of control. Getare *et al.* (2021) reported increased SOC contents in treatments under *Zai* as compared to those under the conventional system. Their findings further revealed that SOC contents were significantly higher in *Zai* treatments that were jointly amended with manure and mineral fertilizer.

In a study to investigate effects of different tillage and fertilization management practices on SOC and its labile organic carbon fractions, Zhao *et al.* (2021) reported that the organic manured treatments significantly increased the concentrations of SOC and its fractions with the significant highest concentrations being recorded in the reduced tillage with organic manure treatments. Particulate organic carbon levels in soil have been used to identify the effects of fertilization practices on soil organic matter in many studies (Wander, 2004). Particulate organic carbon concentrations have been found to be elevated in farming systems relying on organic fertility compared with those using synthetic fertilizers (Li *et al.,* 2018a; Li *et al.,* 2018b; Kirkby *et al.,* 2014; Tong *et al.,* 2014; Yang *et al.,* 2012; Huang *et al.,* 2010; Fortuna *et al.,* 2003; Nissen & Wander, 2003; Wander *et al.,* 1994).

Permanganate oxidizable carbon ($KMnO_4$-C) is the fraction of labile carbon which is obtained from chemical oxidation methods using Potassium permanganate (Blair *et al.,* 1995). It has been considered as an early sensitive index for the impacts of long-term applications of fertilizers or organic resources on the dynamics of the active total soil organic carbon fractions (Xu *et al.,* 2011; Mtambanengwe & Mapfumo, 2008). Previous studies have documented the increased $KMnO_4$-C contents in manure amended soils and also in soils amended with manure and mineral fertilizer (Zhang *et al.,* 2021; Bhardwaj *et al.,* 2019; Yang *et al.,* 2012; Xu *et al.,* 2011; Verma *et al.,* 2010; Blair *et al.,* 2006; Rudrappa *et al.,* 2006).

Yang *et al.* (2012) observed that treatments with double standard rate of manure combined with mineral fertilizer resulted in the highest light fraction organic carbon content, and significantly higher contents of this carbon fraction than all the other treatments. Similarly, Yuan *et al.* (2021) concluded that a high input of organic matter could increase soil light fraction organic carbon after observing high amounts of this carbon fraction in plots treated manure combined with mineral fertilizers. Several studies have reported similar results pointing out increased stocks of light fraction organic carbon in treatments amended with manure either solely or when combined with mineral fertilizer (Mi *et al.,* 2019; Liu *et al.,* 2014; Xu *et al.,* 2011; Yan *et al.,* 2007; Wu *et al.,* 2004; Six *et al.,* 2000; Gregorich *et al.,* 1994; Janzen *et al.,* 1992).

Dissolved organic carbon matter is an important labile fraction since it is the main energy source for soil microorganisms; a primary source of mineralizable nitrogen, phosphorous and sulphur, and it influences the availability of metal ions in soils by forming soluble complexes (Jinbo *et al.,* 2006). It is produced from decomposition of soil organic matter mainly driven by soil microbes (Zhu *et al.*, 2015). Dissolved organic carbon is a measure of carbon easily transportable within ecosystems (Neff & Asner, 2001). Dissolved organic carbon content plays a valuable role in nutrient turnover and the development of microbial populations (Zhu *et al.,* 2015).

According to Poirier *et al.* (2013), manure application directly contributes to the labile organic carbon pool and indirectly affects the conversion of plant residue-carbon into labile forms by enhancing microbial activity. The higher concentrations of dissolved organic carbon in organically amended treatments has been documented in the results reported by numerous previous researchers (Li *et al.,* 2018a; Li *et al.,* 2018b; Liu *et al.,* 2017; Li *et al.,* 2016; Zhu *et al.,* 2015; Liu *et al.,* 2014; Liu *et al.,* 2014b, 2013; Yang *et al.,* 2012; Lou *et al.,* 2011; Xu *et al.,* 2011; Gong *et al.,* 2009). Previous research has also reported higher levels of dissolved organic carbon under practices with minimum to zero tillage (Kumar *et al.,* 2018; Yang *et al.,* 2018; Lewis *et al.,* 2011; Chen *et al.,* 2009).

Numerous studies have reported that changes in soil organic carbon were induced by fertilization practices (Yang *et al.,* 2018, 2012; Wang *et al.,* 2015; Xu *et al.,* 2011; Mucheru-Muna *et al.,* 2007; Yan *et al.,* 2007). However, documented studies to assess the impact of *Zai* pit technology combined with both manure and mineral fertilizer of SOC and its labile fractions remains limited with a with some highlighting the impact of conservation tillage practices on SOC (Liu *et al.,* 2014; Wang *et al.,* 2014).

2.10 Effects of *Zai* pit system combined with ISFM technology on microbial biomass carbon and nitrogen

Soil microbial biomass carbon has been broadly used to assess soil fertility under long-term fertilization regimes (Li *et al.,* 2015). It serves as an indicator of the population of the microbial biomass that does the decomposing (Powlson *et al.,* 2012). In an experimental study conducted an experiment to investigate the effects of biochar amendment and nitrogen fertilization on soil microbial biomass pools, Oladele *et al.* (2019) reported higher microbial biomass pools in treatments with combined organics and nitrogen fertilizer. Chen *et al.* (2017) reported higher soil microbial biomass carbon and nitrogen contents in fertilized treatments than the control.

Comparably in China, the results of a study by Deng *et al.* (2018) showed that the concentrations of both microbial biomass nitrogen and carbon were all significantly increased in treatments of sole application of organics and those with mixed application of chemical fertilizer and organic fertilizer. Similar results were reported by Zhang *et al.* (2017) where the application of sole organic inputs or organics combined with inorganic fertilizers increased soil microbial biomass carbon concentrations compared to the unfertilized control. Likewise, Xu *et al.* (2018) reported highest microbial biomass carbon and nitrogen contents in the combined 30 % organic manure and 70% chemical fertilizer and 60% organic manure and 40 % inorganic fertilizer treatments.

Li *et al.* (2018b) reported a significant increase in microbial biomass carbon concentration with increasing rate of organic manure application in long-term fertilization experiment. Similarly, the results of a study conducted by Li *et al.* (2020) indicated increased microbial biomass carbon in manure amended-treatments as compared to the treatments with chemical fertilizer amendments and the unfertilized control. The results of that experiment demonstrated that long-term application of organic manure alone resulted in a significant increase in microbial biomass carbon compared to mineral-fertilized plots and the control. Li, *et al.* (2018c) reported 102% higher microbial biomass carbon concentrations in treatments with combined manure and mineral fertilizer than that recorded in the control. Comparably, other studies (Li *et al.,* 2020; Kumar *et al.,* 2018; Li, *et al.,* 2018c; Yang *et al.,* 2018, 2012; Naresh *et al.,* 2017; Lou *et al.,* 2011) have reported significant increases in microbial biomass carbon with addition of manure, implying that organic manure, alone or in combination with mineral fertilizers, had favorable impacts on microbial activity, most likely by providing a readily accessible pool of carbon substrate.

The influence of mineral fertilizer on microbial biomass carbon have also been reported in a variety of ways, including positive, negative, and no effects (Ren *et al.*, 2019; Lou *et al.*, 2011; Gong *et al.,* 2009; Xue *et al.,* 2006). Significantly lower microbial biomass carbon concentration has been documented in previous similar studies (Li *et al.,* 2020; Kumar *et al.,* 2018; Gong *et al.,* 2012). Li *et al.* (2018c) in treatments with mineral fertilizer amendments. Kumar *et al.* (2018) reported 38% higher microbial biomass carbon concentrations in treatments with sole mineral Similar.

Significantly higher soil microbial biomass nitrogen have in past been reported under systems characterized by reduced or zero tillage activities than the control (Naresh *et al.*, 2017; Dou *et al.*, 2016; Wang *et al.*, 2015; Wang *et al.*, 2014; Chen *et al.*, 2009; Carpenter-Boggs *et al.,* 2003). By enhancing soil aggregation and minimizing oxidation, zero/reduced tillage methods, such as *Zai* pits, allow carbon to build up in the plow layer, thus increased microbial activities (Carpenter-Boggs *et al.,* 2003).

Xu *et al.* (2018) reported significantly higher soil microbial biomass nitrogen contents in treatments with combined organics and inorganics inputs compared to treatments with sole mineral fertilizers and the untreated controls. According to Liu *et al.* (2017), combined application of chemical fertilizer and organic matter is the best way to increase soil microbial biomass and the resultant nitrogen contents in soil. Li *et al.* (2016) and Oladele *et al.* (2019) also reported significantly high soil microbial biomass nitrogen contents in long-term experiments under combinations of organic and inorganic soil amendment. When comparing manure application to solitary mineral fertilizer application, Pan *et al.* (2009) found that manure application improved soil microbial biomass nitrogen by 49%.

A study by Qiu *et al.* (2016) documented a 12%–48% drop in soil microbial biomass nitrogen with application of mineral fertilizer when compared to the unfertilized control or the initial values. Kallenbach and Grandy (2011) reported contradicting findings where there was no effect on soil microbial biomass nitrogen after application of organic amendment. They pointed out that changes in microbial biomass cannot be as a result of soil amendment with organic inputs only but rather several other factors, such as soil type and climatic condition of the area, all contribute to the overall microbial biomass concentrations. Lentendu *et al.* (2014) and Esperschütz *et al.* (2007) suggested that the response of microbial biomass can be highly variable depending on soil types, management practices, and climate conditions.

Based on the reviewed literature, soil amendment with organic manure either solely or when combined with inorganic fertilizer could be a viable alternative to the difficulties associated with excessive mineral fertilizer application while also boosting soil bio-fertility (Csitári *et al.,* 2021; Furusawa *et al.,* 2019; Wang *et al.,* 2019; Wang *et al.,* 2018; Li *et al.,* 2015; Zang *et al.,* 2015; Pan *et al.,* 2009).

2.11 Conceptual framework

The ASALs of Eastern Kenya are naturally characterized with high temperatures and low erratic rainfall (Jaetzold *et al.,* 2007) which together with inherent and induced deficiencies of major soil nutrients as well as low soil moisture (Kathuli & Itabari, 2015) have led to low agricultural productivity thus rendering the region food insecure. Various water harvesting technologies with nutrient (both organic and inorganic) amendments have been developed throughout the semi-arid areas by non-government organizations (NGO) and researchers (Campbell *et al.,* 2014; Nyamangara *et al.*, 2014; Kaluli *et al.*, 2012; Miriti, 2011; Biamah, 2005). Promoted techniques such as the use of *Zai* Pits in combination with nutrient amendment technologies have been found to minimize the effects of droughts since they ensure soil maintenance, control soil erosion, promote water preservation, increase harvests, increase nutrient use efficiency and agronomic efficiency, reduce runoff by increasing infiltration through creating and enhancing depressional water storage and increase soil biological activities (Getare *et al.,* 2021; Kimaru-Muchai *et al.,* 2020; Mwangi, 2020; Danjuma & Mohammed, 2015). Figure 2.1 shows that the utilization of the *Zai* pit technology coupled with nutrient amendment techniques in Kitui County would result to; Improved soil fertility and moisture retention, increased agricultural production and thus reduction in poverty and food security.

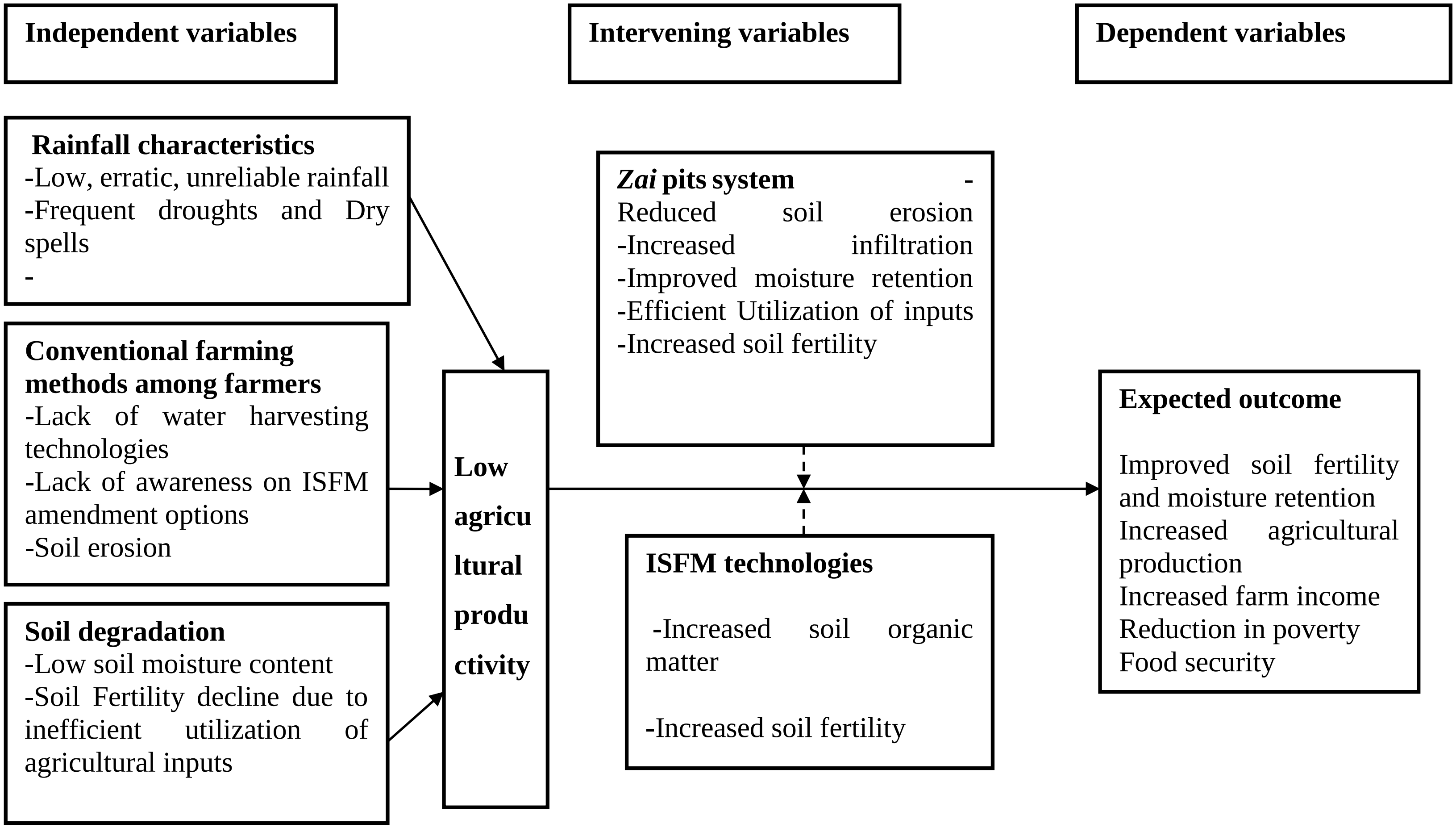


Figure 2.1: Conceptual Framework Source: Modified from the Sustainable Livelihood Framework, DFID (2000), IPCC, (2007) and Nelson t al. (2010).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the study area

The study was carried out in Kitui County, located 180 kilometers East of Nairobi and 105 kilometers East of Machakos, in Eastern Kenya. The County covers an area of 30496 km^2. It borders Machakos and Makueni Counties to the west, Tana River County to the East, Taita Taveta County to the South and Embu and Tharaka Nithi Counties to the North. The County lies between latitudes $0^{0}10'$ and $3^{0}0'$South and longitudes $37^{0}50'$ and $39^{0}0'$ East (Figure 3.1).

The population of the County stood at 1,136,187 persons according to the 2019 census (GOK, 2019). Based on the stratification of the agro-ecological zones, the experiment was set in Kabati to represent the semi-arid areas of Kitui County.

The county consists of an undulating plateau about 1100 m in altitude, surmounted by ridges and hills, which rise to 1700m. The region’s annual precipitation is bimodal, with long rains occurring between March and May (MAM) while the short rains occur between October and December (OND). Annually mean rainfall range between 500 mm to 1150 mm, while the mean annual temperature is 24 degrees Celsius (Jaetzold *et al.*, 2007). The wettest month is November, with an average of 209 mm of rain (Jaetzold *et al.*, 2007) while the hottest months of the year are February and September, with temperatures ranging from 26 to 34 degrees Celsius. The soil types are majorly sandy red and black clay cotton soils (Jaetzold *et al.*, 2007; Republic of Kenya, 2005) which are predominantly vulnerable to erosion, poorly drained and are restricted in their ability to reserve moisture and nutrients.

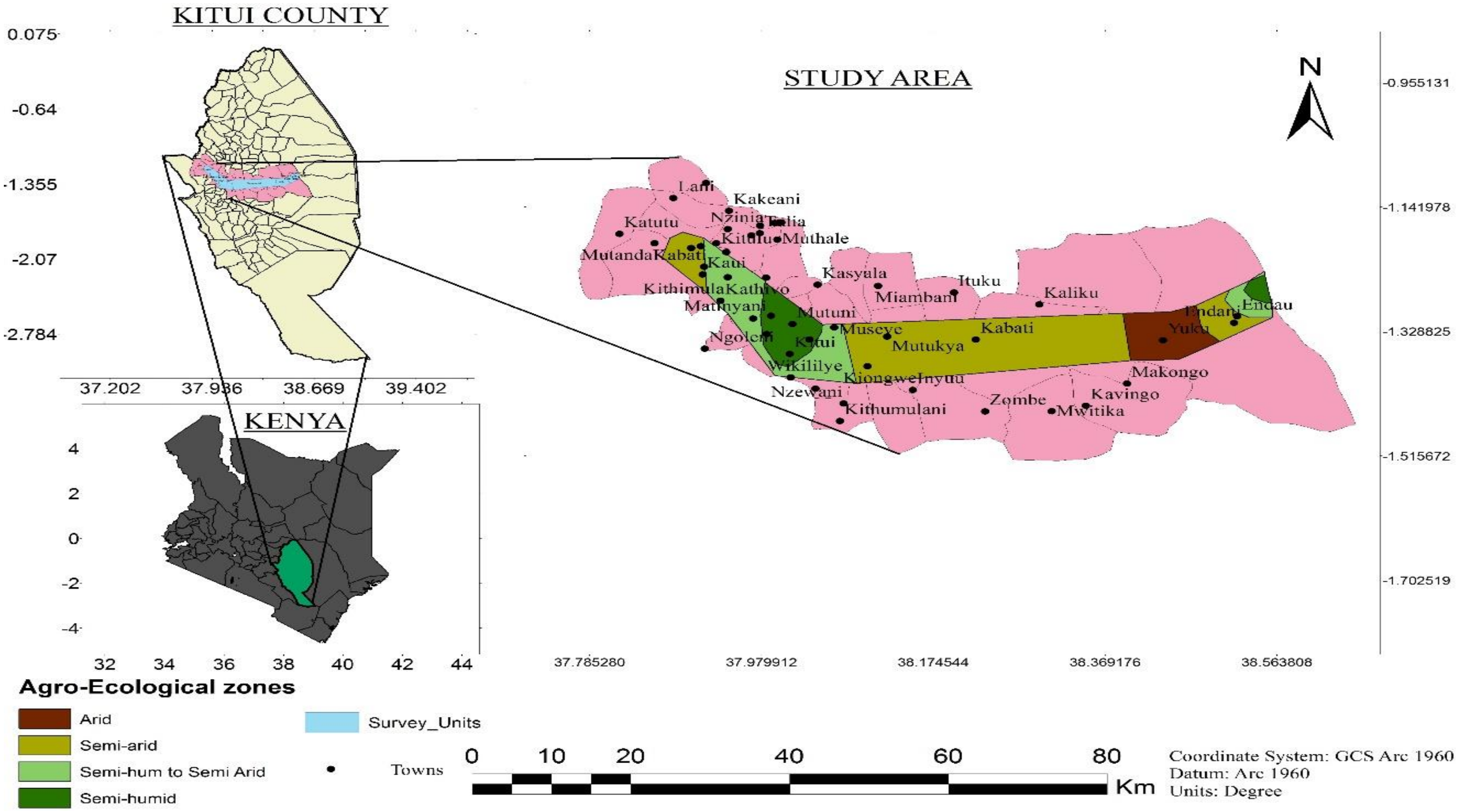


Figure 3.1: Map of Kitui County showing the study area in the semi-arid agroecological zone (Source: ILRIS GIS Database)

Agricultural activities, including livestock rearing and crop production, forms the cornerstone of the local economy and is primarily the major income source for most families (KCIDP, 2018). Maize, beans, sorghum, millet and pigeon peas, are grown primarily for subsistence, whereas green grams, horticultural crops including mangoes, tomatoes, pawpaw, bananas, onions and watermelons and vegetables like spinach and kales are grown primarily for cash generation and home use.

Most farmers practice conventional agriculture, where the land is physically ploughed, and hills and furrows made for sowing using a hand-hoe (NDMA, 2017). This agricultural management practice causes a lot of physical disturbance to the soil particles such as breaking down of macroaggregates (Barto *et al.*, 2010; Lal, 2008). This results to nutrient loss through erosion since the loose soil particles are extremely vulnerable to erosion (Nyamangara *et al.,* 2014). Conventional agricultural practice causes redistribution of organic matter during tillage, thus resulting to reduced stability of soil aggregates therefore increasing their susceptibility to erosion (Mucheru-Muna, *et al.,* 2014; Nyamangara *et al.*, 2014; Nyamadzawo *et al.*, 2013; Verhulst *et al.*, 2010). The conventional practice is also characterized by low soil moisture retention due to high soil water evaporation resulting from the high temperatures (Zelelew *et al.,* 2018; Nyamadzawo *et al.,* 2013). Therefore, the low unreliable rainfall and high temperatures in the area, coupled with the common conventional agricultural practice has led to decreased crop production and even crop failures in some instances (Mucheru-Muna, *et al.*, 2014).

3.2 Site selection and preparation

Using the Kitui County map showing the agroecological zones, Kabati area was selected to represent the semi-arid regions of the County. These regions are characterized by low, erratic and unreliable rainfall, which in most cases are unable to support agricultural production. The soils in the study area are predominantly vulnerable to erosion, poorly drained and are restricted in their ability to reserve moisture and nutrients. The soils in arid and semi-arid regions have also been found to be deficient in nitrogen and phosphorous (Getare *et al.,* 2021) and this informed the fertility amendment component of this study.

The specific study site was selected on the basis that it was land that had not been utilized in the previous ten years. This was done so as to avoid any influence to treatments that may have resulted from previous agricultural activities. The site was cleared of the bushes that existed through the use of pangas and farm jembes. General field measurements were done to ascertain that all experimental plots would fit. Blocks were established, within which experimental plots were randomly laid. Preparation of *Zai* pits in *Zai* plots and planting furrows in conventional plots was done.

Plate 3.1: A plot with *Zai* pits in the experimental site

Plate 3.2: Conventional plots in the experimental site

Plate 3.3: Sorghum plants in a *Zai* pit **Plate 3.4: Sorghum in a conventional plot**

3.3 Experimental design

The field experiments were laid out in a randomized Compete block design (RCBD). Each experimental plot measured 6 m by 4.5 m with a 1 m wide alley separating plots within a block and 2 m wide alley left between blocks. The field experiment ran for four consecutive cropping seasons; short rains 2018 (SR2018) and 2019 (SR2019), and long rains 2019 (LR2019) and 2020 (LR2020). There was a total of 8 treatments (Table 3.1).

The treatments comprised of two systems, either *Zai* pit or convention system (no *Zai* pits), both with four levels of fertilization (no input - control), sole cattle manure, sole mineral fertilizer and both cattle manure and mineral fertilizer). The *Zai* pits measured 60 cm by 60 cm with a 30 cm depth and were spaced at 70 cm and 75 cm inter and intra-row, respectively.

Table 4.1: Experimental treatments during the SR2018, LR2019, SR2019 and LR2020 seasons in Kabati, Kitui County

Technique	ISFM input	N and P from mineral fertilizer (Kg ha^{-1})	N and P from manure (Kg ha^{-1})
Zai pits	Sole Cattle Manure	0	60
Zai pits	Sole Mineral fertilizer	60	0
Zai pits	Cattle Manure + Mineral Fertilizer	30	30
Zai pits	No inputs	0	0
Conventional	Sole Cattle Manure	0	60
Conventional	Sole Mineral fertilizer	60	0
Conventional	Cattle Manure + Mineral Fertilizer	30	30
Conventional	No inputs (control)	0	0

External nutrient amendments were applied, based on the phosphorous and nitrogen contents as determined through a lab analysis of soil samples, at the beginning of every season to give an equivalent amount of 60 kg N ha^{-1} and 60 kg P ha^{-1}, the recommended nitrogen and phosphorous rates in the study area (Karanja *et al.,* 2009; FURP, 1994). Cattle manure (obtained from the South Eastern Kenya University cowshed) was broadcasted at a rate of 10 t ha^{-1} during harrowing for conventional plots but placed in the prepared pits for *Zai* plots, where it was mixed with soil. Mineral fertilizers were pre-weighed for each plot (before going to the field) and applied using dollop cups to ensure uniform distribution within the plot. The fertilizer was directly applied to the furrows in conventional plots and to the planting holes within each *Zai* in *Zai* plots. It was then mixed with soil using small sticks.

Dryland Gadam sorghum variety, whose certified seeds were obtained from the agrovet shops in Kitui town, was used as the experimental test crop. Three seeds were planted per hill at a spacing of 75 cm and 20 cm inter and intra- row (for conventional plots), respectively ((Mwadalu & Mwangi, 2013; KALRO, n.d.). In the *Zai* pits, the seed were planted at a hill spacing of 20 cm totaling to five hills in each *Zai* pits. The seedlings were later thinned out to two seedlings per hill two weeks after emergence to achieve the recommended seed density of 6-8 kg ha^{-1} which is approximately 84000 plants per hectare (Ayako *et al.*, n.d). In each season, hand weeding was done 2 weeks after emergence (when the plant has 2-3 leaves).

3.4 Data collection

3.4.1 Field Measurement of Sorghum Parameters

Data was collected from the vegetative phase to the maturity phase in the course of each season with the following parameters being recorded:

3.4.1.1 Date of Emergence of Plants

Few rows in randomly selected plots were marked and observed to determine the date of emergence. The emerging seedlings were tallied at intervals of 2 days until emergence stopped. Emergence ceased when at least 50% of the plants had the collar of the 5th leaf was visible.

3.4.1.2 Days to 50% Flowering

Excluding the border rows, two rows from all sides of every plot were selected and marked. Sorghum plants in the marked rows were monitored and the dates of 50% flowering were recorded. The date of 50% flowering was identified when at least half of the sorghum plants in the plot showed exposed anthers at the middle of the panicle. Days to 50% flowering were then calculated from the sowing date by deducting the date of sowing from date of 50% flowering.

3.4.1.3 Days to Physiological Maturity

Plants from the marked rows were monitored and the dates of physiological maturity were documented. Maturity was determined by identifying the date of the appearance of a black layer at the point of attachment of the grain to the panicle. This method is an accurate predictor of physiological maturity since it corresponds with the cutoff of assimilates being translocated into the kernel. The date of the black layer is easy to measure since it can be observed in the field without the use of special tools (Eastin *et al.,* 1973). Days to physiological maturity were then obtained by deducting the date of sowing from date of physiological maturity.

3.4.1.4 Grain and stover yield

Sorghum grain and stover were harvested at maturity from all plots under conventional and *Zai* treatments, respectively. The edge effect was minimized by the guard rows that had been planted around the plots and the outside row in all sides of each plot. All panicles were cut at the base of the head using sharp knives (Gesare *et al.,* 2021; Ayako *et al.,* n.d)). The stover was harvested by cutting them off immediately above the ground surface using machetes (Kimaru-Muchai, 2017). The sorghum heads were put in clean sacks and their moisture content determined at the field using a moisture meter (Gesare *et al.,* 2021). The heads were later sun-dried to attain a grain moisture content of 12.5% (KALRO, n.d.), to avoid fungal and insect problems associated with high grain moisture content. Sorghum grains were weighed and expressed as dry matter content while the stover yields were determined on field weight basis immediately after harvesting.

3.4.2 Soil sampling

The initial (pre-experiment) sampling for analyses of selected soil chemical parameters was done beginning of SR2018 season. Following clearing of the land and laying out the experimental plots, soil samples were collected from all experimental plots before establishing the *Zai* pits in *Zai* plots. The final sampling was done at the end of LR2020 season. Soil sampling for analysis of soil aggregate stability, organic carbon fractions and microbial biomass was done once, at the end of the LR2020 season. Using an alderman auger, soil samples were obtained at a soil depth of 0-15 cm (Mucheru-Muna *et al.,* 2014). In all the experimental plots, samples were collected from five spots following a W-shape (Kimaru-Muchai, 2017). They were then bulked into a composite sample, from which a sub-sample was obtained. For aggregate stability, three undisturbed soil samples were obtained at a depth of 0-15cm from randomly selected spots, and from three randomly selected *Zai* pits, across each plot. Samples for soil moisture content analysis were collected after every two weeks at a soil depth of 0-15 cm. All the collected samples were sealed in khaki, marked tags indicating the plot number for easy identification and transferred to the laboratory for analysis.

3.5 Laboratory analyses

Standard methods of manure and soil analysis as described below were used in the determination of soil parameters stated in the four objectives of this study.

3.5.1 Objective one: Analyses of selected soil chemical properties

All the laboratory analyses on the chemical properties of the soil were done using the standard methods for analyzing soils described by Motsara and Roy (2008).

3.5.1.1 Soil pH and electrical conductivity

Using a pH meter, Soil pH was determined at a 1:2.5 soil/water ratio (FAO, 2021; Okalebo *et al.* 2002). 50 g of air-dried soil was added to 50 ml deionised water in a 100 ml glass beaker. The solution was then stirred for 10 minutes and then left to stand for 30 minutes. The sample was stirred again for 2 minutes just before taking pH readings of the soil suspension. The sample was then shaken for 1 minute after which measurement of electrical conductivity were taken. To measure the soil electrical conductivity, an electrical conductivity probe was used. The probe was turned on and inserted into soil-water solution keeping the probe tip well in the center area of the soil suspension. The readings were taken while soil particles were still suspended in solution. To keep soil particles from settling, the solution was stirred gently with electrical conductivity probe. The electrical conductivity reading was recorded after it stabilized. The probe was then turned off and rinsed with distilled water.

3.5.1.2 Total Nitrogen

Nitrogen in soil was determined using Kjeldahl method (Kjeldahl, 1883). About 0.3g of oven dried (105 ^{0}C) soil samples (<0.25 mm) were weighed into labelled, dry and clean digestion tubes. 2.5 ml of digestion mixture (3.2 g of salicylic acid in 100ml of sulphuric acid-selenium mixture) were added to each tube and the reagent blanks for each batch of samples. The samples were then digested at 110 ^{0}C for one hour. They were then removed, cooled and three successive 1-ml portions of hydrogen peroxide were added to them. The temperatures were further raised to 330 ^{0}C and samples allowed to continue heating for 30 minutes. At this point the solution turned colorless. The solutions were allowed to cool after which 25 ml distilled water were added and mixed well until no sediments dissolved. The resultant solution was then allowed to cool and made up to 50 ml with distilled water. The sample were then allowed to settle. Clear sample solutions were read on atomic adsorption spectrophotometer at 65 nm. The total nitrogen (%) was then calculated using equation 1 (Kimaru-Muchai,2017).

$$\%\ Nitrogen\ in\ the\ sample = \frac{V \times N \times 1.4}{W} \qquad Equation\ 1$$

Where, V = acid used in titration (ml)

N = normality of standard acid

W = weight of sample (g)

3.5.1.3 Total organic Carbon

The determination of organic carbon employed the Walkley and Black wet oxidation method (Walkley & Black, 1934) as described by Ryan *et al.* (2001). 0.5grams of air-dried ground (<0.25 mm) soil was weighed into a block digester tube and 5ml of 1 N potassium dichromate solution and 7.5ml of concentrated sulphuric acid added using a burette. The tube was then placed in a pre- heated block at 155^{0}C for 30minutes then left to cool. The digest was then transferred into a 100ml flask and 0.3ml of 1,10-phenanthroline solution (indicator solution) added. A magnetic stirrer was used to stir the solution so as to ensure complete mixing. Ferrous ammonium sulphate solution was used to titrate the digest whereby the end point was reached with a color change from greenish to brown and the titre was recorded. Organic carbon was then calculated using equation 2 (Kimaru-Muchai,2017).

$$\% \, Organic \, carbon = \frac{V_{Blank} - V_{Sample} \, \times \, M \times 3 \times 10^{-3} \times 100}{W_t} \qquad Equation \, 2$$

Where: V_{Blank}=Volume (ml) of ferrous ammonium sulphate solution required to titrate the blank

V_{Sample}=Volume (ml) of ferrous ammonium sulphate solution required to titrate the sample
W_t=Weight (g) of air-dry soil
3×10^{-3}=Equivalent weight of carbon
100=percentage
M=Molarity of ferrous ammonium sulphate solution (approximately 0.5M i.e., $10/V_{blank}$).

3.5.1.4 Extractable phosphorous (P)

Extractable phosphorus was determined using the Bray and Kurtz P-1 soil test phosphorus (P) method (Bray & Kurtz, 1945). In this procedure, 2 g of oven dried soil were weighed into a 50 ml volumetric flask. 20 mL of Bray and Kurtz P-1 extracting solution (0.025M HCl in 0.03 M NH_4F) were added to each flask and shaken at 200 rpm for five minutes at room temperature. The extracts were then filtered through Whatman filter paper No. 42. Analysis of phosphorous was done by colorimetry using a blank and standards prepared in the Bray P-1 extracting solution. A calibration curve was plotted for standards, plotting absorbance against the respective phosphorous concentrations. P concentration were read in the unknown samples from the calibration curve and Bray and Kurtz P-1 extractable phosphorus calculated using equation 3 (Kimaru-Muchai,2017).

$$Extractable\ P\ (mgP/kg\ soil) = \frac{C_p\ x\ [0.020\ L\ extract]}{0.002\ kg\ soil} \qquad Equation\ 3$$

Where C_p = = Concentration of P in Bray and Kurtz P-1 extract, in mg/L.

3.5.2 Objective two: Soil aggregate stability and moisture content analyses

3.5.2.1 Aggregate stability

In the laboratory, samples for analysis of stability of aggregates were air-dried at room temperature for 24 hours before sieving for stability tests. Dry-sieving method, described by Gartzia-Bengoetxea *et al.* (2009) was employed in the determination of aggregate stability expressed as mean weight diameter (MWD). After air drying, three soil samples for each plot were thereafter passed through an 8mm sieve to remove coarse plant residues, root pieces, and stones and other materials greater than 8 mm in diameter. 50g of dry soil samples were placed on a set of seven nested sieves of 3.35 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.18 mm and 0.063 mm (Table 3.3). For 2 minutes, the sieves were then mechanically shaken to segregate the soil into the following aggregate size classes as described by (Briar *et al.*, 2011): >2.0 mm large macro aggregates (>2 mm); macro aggregates (2-1mm); small macro-aggregates (1-0.25 mm); and micro aggregates, silt and clay fractions (<0.25 mm). The fractionated samples were blended together to make compounded samples for each class of aggregate sizes. Mean weight diameter was calculated using equation 4 below (Kimaru-Muchai,2017).

$$\mathrm{MWD} = \sum_{i=1}^{7} XW_i \qquad Equation\ 4$$

Where X is the mean diameter of aggregates remaining on the different sieves, W_i denotes the ratio of aggregate weight remaining on the sieve to total sample weight, and 7 refers to the number of sieves employed for aggregate separation.

3.5.2.2 Soil moisture content

Gravimetric method described by Ryan *et al.* (2001) was used to determine soil moisture content. In the laboratory, soil samples were oven-dried at 105°C for a period of 24–48 hours. Soil water concentration was determined by the difference between the oven-dry mass and the initial field mass of soil samples. The difference in mass was the total soil moisture in the sample, which was then converted to volumetric units using soil density. The percentage moisture content was calculated using equation 5 (Kimaru-Muchai,2017).

$$\%\ \text{Moisture content} = \frac{\text{Sample fresh weight} - \text{Sample dry weight} \times 100\%}{\text{Sample dry weight}} \qquad Equation\ 5$$

3.5.3 Objective three: Laboratory analyses for selected labile organic carbon fractions

3.5.3.1 Particulate organic carbon (POC)

Particulate organic carbon was determined by modifying the method described by Cambardella and Elliott (1993). Soil (10 g) was dispersed in 30 ml of sodium hexametaphosphate (5 g L^{-1}) and shaken for approximately 18 hours. The suspended soil was poured over a 0.053 mm sieve and rinsed three times with a weak stream of distilled water to ensure complete separation. Particles left on the sieve were transferred to dry beakers, oven-dried at 60 ^{0}C for 48 hours, weighed, and then ground to determine organic carbon content using the modified Walkley-Black (Walkley & Black, 1934) method as described above.

3.5.3.2 Permanganate oxidizable carbon (KMnO4-C)

Permanganate oxidizable carbon (KMnO4-C) proportion was determined following the procedure described by Si *et al.* (2022) and Blair *et al.* (1995). Soil samples (equivalent to 15 mg of soil organic carbon) were oxidized with 25 ml of 333 mM $KMnO_4$ by shaking for one hour. The tubes were then centrifuged at 3500 rpm for 5 minutes. The supernatants were diluted 1:500 and their absorbances were measured at a wavelength of 565 nm using a spectrophotometer. The change in the $KMnO_4$ concentration was used to estimate the amount of carbon oxidized in the soil sample.

3.5.3.3 Light fraction organic carbon

For the light fraction organic carbon, 10g air-dried soil was placed into a 100 ml centrifuge tube containing 30 ml NaI (1.80 g.cm^{-3}). On a shaker, the tube was shaken at 200 rpm for 1 hour and centrifuged for ten minutes at 1000 rpm. The upper solution was then filtered using a 0.45 μm cellulose-acetate filter. The remainder soil on the filters were rinsed three times using 0.01 M calcium chloride and distilled water and then dried at 60 ^{0}C for 48 hours, weighed, and ground to pass through a 0.15 mm sieve (Cambardella & Elliott, 1993). The amount of organic carbon was determined using the method described in section 3.5.1.3 for total soil organic carbon.

3.5.3.4 Dissolved organic carbon

Dissolved organic carbon was measured by adding 50 ml of distilled water to 10 g of fresh soil (5:1, v/w) in a 200 ml polypropylene bottle. For 30 minutes, the samples were shaken at 250 revolutions per minute (rpm) and then centrifuged for 10 minutes at 10,000 rpm. The upper suspension was filtered through a 0.45μm filter into a bottle. The carbon content in the filtered solution was determined using Walkley-Black method (Walkley & Black, 1934) as described above.

3.5.4 Objective four: Analyses of soil microbial biomass (C and N)

Soil microbial biomass was determined using fumigation-extraction (Jenkinson & Powlson, 1976) technique which subjects soil to chloroform fumigation that results in microbial cell wall lyses, allowing the cellular contents to become extractable in 0.5 M K_2SO_4.

3.5.4.1 Pre-incubation preparation

In order to activate soil microorganisms, about 200 g of soil sub-samples were weighed and the water holding capacity adjusted to 45% field capacity. The soil sub samples were then incubated at 25^{0}C for 7 days in the dark to permit uniform rewetting and to allow microbial activity to equilibrate after initial disturbance.

3.5.4.2 Laboratory fumigation

Chloroform fumigation was carried out according to the procedure described by Brookes *et al.* (1985). This was done by weighing in duplicates 15 g of previously pre-incubated soil into a 50 ml beaker. The samples were placed into two-paired desiccators, one with a 50 ml beaker containing 25 ml of alcohol-free chloroform and the other free from chloroform to serve as nonfumigated control. The aim of the alcohol-free chloroform was to kill the soil microbes while the free alcohol would eliminate the possibility of any other source of carbon apart from the lysed microbes in the soil. The desiccators were tightly closed after adding chips to assist in volatilization of the chloroform and stored under dark conditions for 72 hours at room temperature. The samples were then removed after evacuating the desiccators repeatedly (8-12 times) using a vacuum pump.

3.5.4.3 Soil extraction

Extraction was done by transferring 15 g of the fumigated and non-fumigated (control) soil samples (obtained in section 3.4.4.2 above) into 125 ml shaking bottles and adding 50 ml of 0.5 M K_2SO_4. The samples were then shaken on a wrist action shaker for 25 minutes at 150 rpm and subsequently filtered using Whatman filter paper No. 42 to give a clear extract for microbial C and N determination.

3.5.4.4 Determination of soil microbial biomass carbon

Determination of soil microbial biomass carbon was done by adding 2 ml of 0.16 M ~$K_4S_2O_8$ and 10 ml of concentrated H_2SO_4 into 10 ml of the sample extract obtained in section 3.5.4.3 above. The resultant contents were mixed using a vortex mixer and then heated in the block digester for 30 minutes at 150 ^{0}C. Total soluble C (soil available carbon) was determined colorimetrically at 600 nm and was calculated as (Kimaru-Muchai,2017):

$$Total\ Soluble\ C = Carbon_{non-fumigated} \qquad Equation\ 6$$

Whereas, soil microbial biomass carbon was calculated by subtracting unfumigated soil organic content from fumigated ones (Vance *et al.,* 1987; Brookes *et al.,* 1985) as shown in equation 7:

$$\text{Microbial Biomass C} = (\text{C}_{\text{fumigated}} - \text{C}_{\text{control}}) \qquad Equation\ 7$$

3.5.4.5 Determination of soil microbial biomass nitrogen

Determination of soil microbial biomass nitrogen was done by adding boric acid as the oxidizing reagent to 10ml sample of soil extracted in section 3.5.4.3. Both organic-N and ammonium-N was oxidized to nitrate, and total N was then determined by adding 1.0ml of 5% salicylic acid and 10ml of 16% NaOH while mixing. After cooling, nitrogen was colorimetrically read at 410 nm and soil microbial biomass nitrogen was calculated by subtracting unfumigated soil N content from fumigated ones (Vance *et al.,* 1987; Brookes *et al.,* 1985) as shown in equation 8 (Kimaru-Muchai,2017);

$$\text{Microbial Biomass N} = (\text{N}_{\text{fumigated}} - \text{N}_{\text{control}}) \qquad Equation\ 8$$

3.5.5 Manure analysis

Analysis of cattle manure was done at the beginning of the experiment using standard methods to determine the phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and total nitrogen (N) contents of the manure. The P, K, Ca and Mg contents were determined by microwave-assisted acid digestion as described by Wolf *et al.* 2003. Total nitrogen content was determined using the Kjeldahl method (Kjeldahl, 1883) as described in section 3.5.1.2.

3.6 Statistical analysis

Both sorghum yield and soil data were subjected to a two-way analysis of variance (ANOVA) using R-studio program version 1.3.1073 to obtain f values. Pair-wise comparison of selected soil parameters differences between the start and the end of the experiment were analyzed using t-test. Differences between treatment means were separated using least significance difference (LSD) at $p \leq 0.05$.

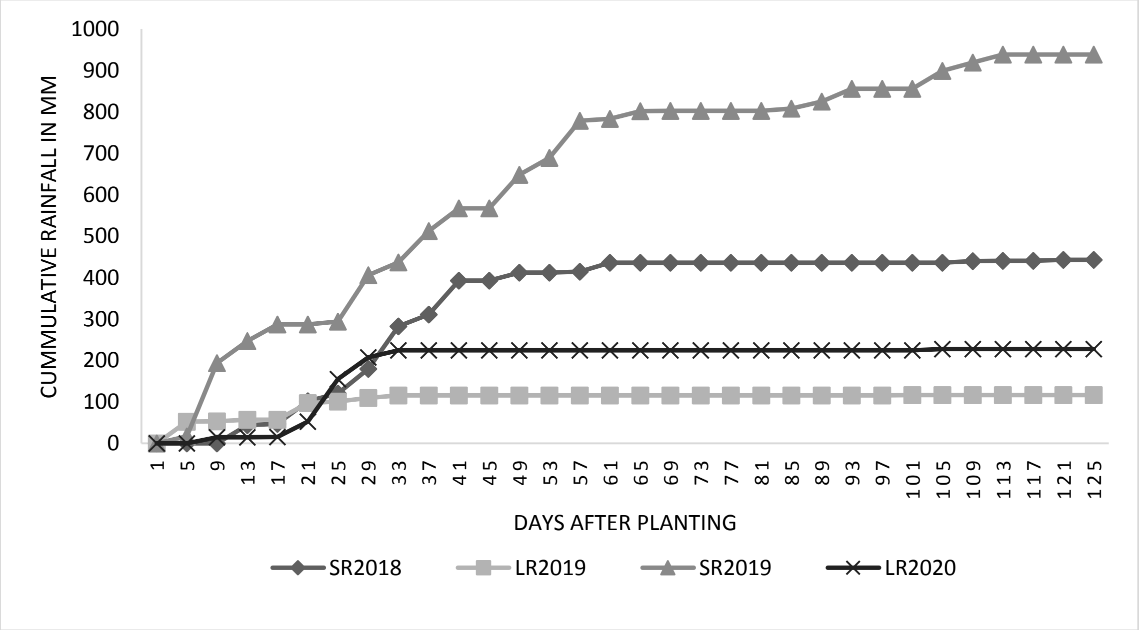
CHAPTER FOUR

4.0 RESULTS

4.1 Effects of *Zai* pit technology combined with selected ISFM amendment options on selected soil chemical properties

4.1.1 Rainfall characteristics and distribution during the SR2018, LR2019, SR2019 and LR2020 experimental seasons

There was seasonal rainfall variability over the four study seasons (Figure 4.1). The four consecutive cropping seasons SR2018, LR2019, SR2019, and LR2020 were characterized by different rainfall patterns, with higher rainfall occurring in the short rainy seasons (SR2019-938.1 mm and SR2018- 442.71 mm) compared to the long rainy seasons (LR2019-116.3mm and LR2020- 228mm) (Figure 4.1).



(SR2018= Short rains season in the year 2018, LR2019= Long rains season of the year 2019, SR2019= Short rains season in the year 2019, LR2020= Long rains season in the year 2020)

Figure 4.1: Rainfall distribution at different days after planting during the SR2018, LR2019, SR2019 and LR2020 seasons in Kabati, Kitui County

SR2018 and SR2019 seasons recorded the highest rainfall events (87.2 mm and 100.3 mm) on the 32nd and 29th days, respectively while the highest rainfall events for LR2019 (40 mm) and LR2020 (64 mm) seasons were recorded on the 19th and 23rd days, respectively (Figure 4.1).

Total daily rainfall recorded during the four study seasons ranged from 0.01 mm- 87.2 mm, 0.5 mm- 40 mm, 0.4 mm- 100.3 mm and 1 mm- 64 mm for SR2018, LR2019, SR2019 and LR2020, respectively, (Table 4.1). The total number of rainy days varied in the four growing seasons with SR2019 having the highest number of rainy days (47 days) followed by SR2018 (31 days). However, LR2019 and LR2020 had the lowest number of rainy days, 10 and 11, respectively (Table 4.1).

Much of the rainfall during the SR2018 and SR2019 seasons was received during the first two months with a prolonged dry spell period occurring from day 64 after planting and prolonging towards the end of the planting seasons (Table 4.1). In Contrast, the long rains seasons (LR2019 and LR2020) experienced interchanging periods of rainy days and consecutive dry days during the first month. An intra-seasonal dry spell of 73 days and 69 days was experienced during the LR2019 and LR2020, respectively, whereas during the SR2018 and SR2019 drought periods of 43 days and 14 days, respectively, were experienced.

In all the four seasons, there were scenarios of agricultural dry spells that were experienced within the growing seasons. Similar to other studies (Usman & Reason, 2004; Barron *et al.,* 2003; Fox & Rockström, 2000), this study defined dry spell as a period of consecutive 5-10 dry days with a less than 5 mm total amount of rainfall resulting in a soil water deficit causing crop water stress.

Table 4.1: Seasonal rainfall characteristics for 2018 and 2019 short rains and the 2019 and 2020 long rains seasons

	Seasons			
Parameter	**SR2018**	**LR2019**	**SR2019**	**LR2020**
Rain on-set	17/11/2018	26/4/2019	16/10/2019	5/4/2020
End of season	3/3/2019	19/5/2019	2/2/2020	1/5/2020
Length of rainfall season (days)	31	10	47	11
Total rainfall received (mm)	442.7	116.3	938.1	228
Minimum daily rainfall (mm)	0.01	0.5	0.4	1
Maximum daily rainfall (mm)	87.2	40	100.3	64
Rainfall received (mm)-5 to 10 days	0	23.8	222.6	15
11 to 15 days (mm)	47.5	3.8	27.8	1
After 15 days (mm)	395.2	59.1	670.3	212
Dry spell periods (days)	43	73	14	69

(SR18-=short rains 2018, LR19= long rains 2019, SR19= short rains 2019, LR20= long rains 2020)

In all the four seasons, Sowing was conditioned upon the previous day having received significant rainfall (minimum of 30 mm) so as to wet the soil, provided that no dry spell of 5 days or more occurred in the week after that date. This ensured sufficient soil moisture to support sorghum seed germination.

A major dry spell was experienced in the LR2019 season from day 27 to day 100 after planting. This dry spell (0mm rainfall) coincided with the flowering period during this season and therefore resulted to an almost complete failure in sorghum germination. Dry spell scenarios were also experienced in the other three study seasons (SR2018, SR2018 and LR2020). However, these dry spells were not as detrimental to sorghum production as was the case in LR2019 since they occurred from day 64 after planting in all the three seasons. Here, 100% flowering had already occurred and seed development was already taking place.

4.1.2 Initial soil chemical characteristics in the study site

The initial soil chemical characteristics, established through a laboratory analysis of pre-experiment soil samples, are as shown in table 4.2 below. The soils in the study area were acidic with a pH value of 5.5.

Table 4.2 : Initial soil chemical characteristics (0–15 cm) at Kabati experimental site, Kitui County, Kenya (Pre-experiment)

Soil parameters	values
Soil pH (H_2O)	5.5
Total nitrogen (%)	0.4
Total organic carbon (%)	1.3
Extractable Phosphorous (ppm)	10.0
Electrical conductivity (mS/m)	208.9

The initial values for percentage total nitrogen and total organic carbon were 0.37 and 1.33, respectively.

4.1.3 Average nutrient composition (%) of cattle manure used

The average nutrient composition of cattle manure used during the four experimental seasons are as shown in table 4.3. The cattle manure had a pH of 7.6 and available phosphorous of 0.4%.

Table 4.3: Average nutrient composition (%) of cattle manure applied in the soil during the experimental period at Kabati, Kitui County, Kenya.

Parameters	Amounts (%)
pH-Water	7.6
Total Nitrogen	1.1
Available phosphorous	0.4
Potassium	1.0
Magnesium	0.5
Calcium	1.3

4.1.4 Soil pH

Generally, there was variation in pH levels across the treatments, with all treatments that had manure application increasing while those with sole application of mineral fertilizer decreasing at the end of the experiment (Table 4.4). The influence on soil pH was statistically significant at $p \leq 0.05$ in *Zai* with manure ($p = 0.02$), conventional tillage system with manure ($p \leq 0.05$), *Zai* pit with manure and half rate mineral fertilizer ($p = 0.03$) and conventional with manure and half rate mineral fertilizer ($p \leq 0.05$) (Table 4.4). The difference between treatments was significant at $p = 0.01$ at the end of the experiment. *Zai* with combined manure and inorganic fertilizer (ZM30F30) recorded a significantly higher pH value compared to its similar treatment under conventional system.

Among the treatments under conventional system, at the end of the experiment, conventional tillage system with sole manure (CM60) recorded the highest significant ($p=0.01$) pH value, which was 10%, 2% and 6% higher than CF60, CM30F30 and CNO treatments, respectively. *Zai* with sole manure (ZM60) recorded 8%, 11% and 1% significantly higher pH value than *Zai* with no input (ZNO), *Zai* with sole mineral fertilizer (ZF60) and *Zai* with combined manure and chemical fertilizer (ZM30F30), respectively (Table 4.4). Generally, the interaction effect on soil pH between the farming system and the selected nutrient amendment options was significant in treatments under *Zai* technology as opposed to similar treatments under conventional system.

Table 4.4: Soil pH (0-15 cm) at the start of 2018 short rains and end of 2020 long rain seasons at Kabati, Kitui County

Soil Parameter	**Soil pH**		
Treatments	**Start of experiment (before nutrient application)**	**End of experiment (after nutrient application)**	**t-test**
ZNO	5.40^{a}	5.45^{bc}	2.76
CNO	5.44^{a}	5.55^{b}	1.35
ZM60	5.59^{a}	5.89^{a}	4.71*
CM60	5.58^{a}	5.88^{a}	3.46*
ZF60	5.49^{a}	5.25^{c}	4.1
CF60	5.43^{a}	5.32^{c}	3.96
ZM30F30	5.59^{a}	5.82^{a}	5.42*
CM30F30	5.53^{a}	5.78^{ab}	4.04*
LSD	0.33	0.42	
P-value	0.74	0.0128*	

Means with same superscript letters in the same column denote no significant difference between treatments at $p \leq 0.05$ *(*=significant at $p \leq 0.05$ between SR2018 and LR2020 seasons, LSD= Least significant differences between* means, *ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+ 60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}).*

4.1.5 Electrical conductivity

Electrical conductivity significantly increased at $p \leq 0.05$ in all the treatments (Table 4.5); *Zai* pit with no input (p=0.02), *Zai* pit with manure (p= 0.02), *Zai* pit with full rate fertilizer (p=0.01), *Zai* pit with both manure and half rate mineral fertilizer (p= 0.01), conventional system with no input ($p \leq 0.05$), conventional system with manure (p= 0.01), conventional system with full rate mineral fertilizer (p= 0.02) and conventional system with both manure and half rate mineral fertilizer ($p \leq 0.05$).

All the treatment under *Zai* pit system had a significant ($p \leq 0.05$) positive effect on electrical conductivity of soil as compared to their similar under conventional system. *Zai* with full rate mineral fertilizer significantly (p=0.02) increased electrical conductivity by 6% compared to conventional system with sole mineral fertilizer.

Zai with no input and *Zai* with sole cattle manure recorded 28% and 6% significantly higher ($p \leq 0.05$) electrical conductivity values compared to conventional system with no input and conventional system with sole cattle manure, respectively.

Among the treatments under *Zai* pit technology, *Zai* with no input recorded the highest significant ($p \leq 0.05$) electrical conductivity value at the end of the experiment and this was 3%, 7% and 9% higher than *Zai* with sole manure, *Zai* with sole mineral fertilizer and *Zai* combined with combined manure chemical fertilizer, respectively (Table 4.5).

Conventional with combined manure and mineral fertilizer recorded the highest significant electrical conductivity value among all the treatments under conventional system, which was, 7%, 12% and 26% higher than conventional with sole manure, conventional with sole chemical fertilizer and the control, respectively (Table 4.5).

Table 4.5: Soil electrical conductivity (0-15 cm) at the start of 2018 short rains and end of 2020 long rain seasons at Kabati, Kitui County

Soil Parameter	**Electrical Conductivity (mS/m)**		
Treatments	**Start of experiment (before nutrient application)**	**End of experiment (after nutrient application)**	**t-test**
ZNO	249.8 ^{a}	394.7 ^{a}	5.38*
CNO	183.8 ^{a}	298.4 ^{d}	10.76*
ZM60	209.9 ^{a}	383.4 ^{ab}	4.45*
CM60	194.1 ^{a}	360.1 ^{bc}	8.84*
ZF60	210.7 ^{a}	366.8 ^{bc}	6.23*
CF60	192.3 ^{a}	343.8 ^{c}	9.60*
ZM30F30	200.2 ^{a}	360.5 ^{c}	8.59*
CM30F30	234.8 ^{a}	388.0 ^{a}	9.15*
LSD	62.28	30.91	
P-value	0.28	0.02127*	

Means with same superscript letters in the same column denote no significant difference between treatments at $p \leq 0.05$ *(*=significant at $p \leq 0.05$ between SR2018 and LR2020 seasons, LSD= Least significant differences between* means, *ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+ 60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}).*

4.1.6 Total nitrogen

At the end of the experiment, total nitrogen significantly $p \leq 0.05$ decreased in *Zai* pits with no input, *Zai* pit with full rate manure, *Zai* pit with both half rate manure and mineral fertilizer, conventional tillage with full rate manure, conventional system with full rate mineral fertilizer and conventional system with both half rate manure and mineral fertilizer (Table 4.6).

The results revealed a significant ($p = 0.01423$) difference between treatments at the end of the experiment (Table 4.6). The results revealed that the observed significant differences in mean existed in the ZNO vs CNO and ZMF30 vs CMF30 treatments. *Zai* with no input and *Zai* with sole mineral fertilizer significantly ($p = 0.01$) increased total nitrogen by 17% and 6% as compared to the conventional system with no input (control) and conventional system with sole mineral fertilizer.

Conventional system with cattle manure and half rate fertilizer had a significant positive effect on total nitrogen and this was higher by 21% than *Zai* with cattle manure and half rate mineral fertilizer (Table 4.6). Among the *Zai* treatments, *Zai* with no input recorded the highest value for total nitrogen which was greater by 5%, 17% and 11% than *Zai* with sole manure, *Zai* with sole chemical fertilizer and *Zai* with combined manure and mineral fertilizer, respectively.

Conventional system with combined manure and mineral fertilizer recorded the highest significant value for total nitrogen and this was 27%, 10% and 33% higher than conventional with no input, conventional system with sole manure and conventional system with sole mineral fertilizer, respectively (Table 4.6).

Table 4.6: Total nitrogen (%) (0-15 cm) at the beginning of 2018 short rains and end of 2020 long rain seasons at Kabati, Kitui County

Soil Parameter	**Total Nitrogen (%)**		
Treatments	**Start of experiment (before nutrient application)**	**End of experiment (after nutrient application)**	**t-test**
ZNO	0.33^{a}	0.19^{b}	14.13*
CNO	0.31^{a}	0.16^{c}	3.44
ZM60	0.38^{a}	0.18^{bc}	6.27*
CM60	0.31^{a}	0.19^{b}	4.99*
ZF60	0.46^{a}	0.16^{c}	2.74
CF60	0.39^{a}	0.15^{cd}	10.78*
ZM30F30	0.38^{a}	0.17^{bc}	4.13*
CM30F30	0.38^{a}	0.21^{a}	5.31*
LSD	0.16	0.03528	
P-value	0.47	0.01423 *	

Means with same superscript letters in the same column denote no significant difference between treatments at $p \leq 0.05$ *(*=significant at $p \leq 0.05$ between SR2018 and LR2020 seasons, LSD= Least significant differences between* means, *ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+ 60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}).*

4.1.7 Total organic carbon (TOC)

Significant ($p \leq 0.05$) increases in total organic carbon between the beginning and end of the experiment were recorded under *Zai* pit with sole cattle manure treatment (p= 0.04), conventional with sole cattle manure treatment (p= 0.04) and conventional with no input treatment (p= 0.03). *Zai* with total manure recorded a 12% significantly ($p \leq 0.05$) higher total organic carbon value as opposed to conventional with sole manure (Table 4.7).

Table 4.7: Total organic carbon (%) (0-15 cm) at the beginning of 2018 short rains and end of 2020 long rain seasons at Kabati, Kitui County

Soil Parameter	**Total Organic Carbon (%)**		
Treatments	**Start of experiment (before nutrient application)**	**End of experiment (after nutrient application)**	**t-test**
ZNO	1.33^{a}	1.57^{a}	-1.03
CNO	1.07^{a}	1.65^{a}	-3.07*
ZM60	1.12^{a}	1.91^{a}	-4.49*
CM60	1.35^{a}	1.69^{a}	-3.16*
ZF60	1.37^{a}	1.51^{a}	-0.56
CF60	1.28^{a}	1.55^{a}	-1.06
ZM30F30	1.36^{a}	1.60^{a}	-1.32
CM30F30	1.44^{a}	2.22^{b}	-1.52
LSD			
P-value	0.59	0.24	

Means with same superscript letters in the same column denote no significant difference between treatments at $p \leq 0.05$ *(*=significant at $p \leq 0.05$ between SR2018 and LR2020 seasons, LSD= Least significant differences between* means, *ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+ 60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}).*

Under the *Zai* pit system, *Zai* with sole cattle manure increased Total organic carbon by 36%, 22% and 19% higher as compared to *Zai* with full rate mineral fertilizer, *Zai* with no input and *Zai* with cattle manure and half rate mineral fertilizer respectively (Table 4.7). Among the treatments under conventional system, conventional with combined manure and mineral fertilizer recorded 29%, 27% and 36% significantly ($p \leq 0.05$) higher values of TOC as compared to the control, conventional with sole manure and conventional with sole chemical fertilizer, respectively (Table 4.7).

4.1.8 Extractable phosphorous

The amount of extractable phosphorous significantly ($p \leq 0.05$) increased at the end of the LR2020 season in *Zai* with sole cattle manure ($p = 0.02$), *Zai* with full rate mineral fertilizer ($p=0.01$), *Zai* with cattle manure and half rate mineral fertilizer (0.021 and conventional system with combined cattle manure and mineral fertilizer ($p=0.04$). At the end of the experiment, *Zai* with no input, *Zai* with sole manure, *Zai* with sole mineral fertilizer and *Zai* with combined manure and mineral fertilizer treatments significantly ($p=0.02$) increased phosphorous when compared to conventional with no input, conventional with sole manure, conventional with sole mineral fertilizer and conventional with combined manure and mineral fertilizer by 3%, 8%, 123% and 63%, respectively (Table 4.8).

Conventional with combined manure and mineral fertilizer recorded the highest significant value for extractable phosphorous among the treatments under the conventional system and this was 33%, 8% and 53% higher than the control, conventional with sole manure and conventional with sole inorganic fertilizer, respectively (Table 4.8). Among the treatments under *Zai* system, *Zai* with sole fertilizer recorded the highest significant value for extractable phosphorous and this was higher than *Zai* with no input, *Zai* with sole manure and *Zai* with combined manure and mineral fertilizer by 107%, 83%, and 23%, respectively (Table 4.8).

Table 4.8: Extractable Phosphorous (ppm) (0-15 cm) at the beginning of 2018 short rains and end of 2020 long rain seasons at Kabati, Kitui County

Soil Parameter	**Extractable Phosphorus (ppm)**		
Treatments	**Start of experiment (before nutrient application)**	**End of experiment (after nutrient application)**	**t-test**
ZNO	12.8^{a}	20.4^{c}	-2.05
CNO	8.84^{a}	19.78^{c}	-2.27
ZM60	11.02^{a}	27.7^{bc}	-3.69*
CM60	7.10^{a}	25.59^{bc}	-2.49
ZF60	10.2^{a}	66.97^{a}	-6.97*
CF60	6.37^{a}	16.01^{c}	-4.35
ZM30F30	8.74^{a}	53.31^{ab}	-1.86*
CM30F30	15.3^{a}	27.7^{bc}	-4.32*
LSD	36.95	31.95	
P-value	0.1047	0.0179*	

Means with same superscript letters in the same column denote no significant difference between treatments at $p \leq 0.05$ *(*=significant at $p \leq 0.05$ between SR2018 and LR2020 seasons, LSD= Least significant differences between* means, *ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+ 60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}).*

4.2 Effects of *Zai* pit technology combined with selected ISFM amendment options on sorghum grain and stover yields

4.2.1 Effects on phenological parameters

4.2.1.1 Effect of treatments on days to emergence after sowing

Effect of treatments on days to emergence across the four study seasons is shown in Table 4.9. The difference between treatments within each season was not significant at $p \leq 0.05$. Generally, days to emergence after sowing were less in short rain seasons (SR2018 and SR2019) compared to long rain seasons (LR2019 and LR2020). Days to emergence ranged between 9- 11 days and 9- 10 days for SR2018 and SR2019 seasons. More days to emergence were required in the long rain seasons with days ranging between 15- 17 days for both the LR2019 and LR2020 seasons.

Emergence occurred 6 days earlier in the SR2018 and SR2019 seasons (10 days) compared to the LR2019 and LR2020 seasons (16 days). Across the four seasons, days to emergence were generally fewer in treatments under *Zai* system compared to those under conventional system. Similarly, treatments with inorganic amendments recorded fewer days to emergence after sowing compared to those with sole mineral fertilizer and those with no amendments in treatments under both *Zai* and conventional systems (Table 4.9).

In SR2018, both *Zai* with sole manure and *Zai* with manure combined with half rate mineral fertilizer recorded fewer days (9 days) to emergence which was 20% lesser than the days recorded in conventional with sole manure and conventional with manure combined with half rate mineral fertilizer (11 days). In the LR2019 season, Gadam sorghum took an extra of one (1) average day to mature in conventional with no input treatment (17 days) compared to the treatment under *Zai* with no input (16 days). In LR2020, the crop emerged faster in *Zai* with sole manure and *Zai* with manure combined with mineral fertilizer (15 days) compared to similar treatments under conventional system (17 days).

Table 4.9: Duration of Gadam sorghum growth from sowing to emergence expressed in calendar days

Stage	Treatment	Calendar days			
		SR2018	**LR2019**	**SR2019**	**LR2020**
1st Germination	ZNO	10 ^{a}	16 ^{a}	10 ^{a}	17 ^{a}
	ZM60	9 ^{a}	15 ^{a}	10 ^{a}	15 ^{a}
	CM60	11 ^{a}	17 ^{a}	9 ^{a}	17 ^{a}
	CNO	11 ^{a}	17 ^{a}	9 ^{a}	16 ^{a}
	ZF60	10 ^{a}	15 ^{a}	10 ^{a}	15 ^{a}
	CF60	11 ^{a}	16 ^{a}	9 ^{a}	16 ^{a}
	ZM30F30	9 ^{a}	15 ^{a}	10 ^{a}	15 ^{a}
	CM30F30	11 ^{a}	16 ^{a}	10 ^{a}	17 ^{a}
	P-value	0.71	0.17	0.25	0.17

ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+ 60 kg N ha^{-1}*, CF60=Conventional+ 60 kg N ha*$^{-1}$*, ZM30F30=Zai+ Cattle manure+ 30 kg N ha*$^{-1}$*, CM30F30=Conventional + Cattle Manure + 30 kg N ha*$^{-1}$*).*

4.2.1.2 Effect of treatments on days to 50% flowering after sowing

The effect of treatments on days to 50% flowering of Gadam sorghum is presented in Table 4.10. There was no significant difference amongst the treatments in the days to 50% flowering. In the SR2018 and SR2019 short rain seasons, days to 50% flowering ranged from 60- 64 days between different treatments. More days to 50% flowering were required in the LR2019 and LR2020 long rains seasons with days ranging from 70- 74 and 71- 76, respectively.

Generally, more days to 50% flowering were recorded in the long rain seasons (LR2019 and LR2020) compared to the days recorded in the two short rain seasons (SR2018 and SR2019). Seasonal effect portrayed a slower crop development by delaying days to 50 % flowering with an average of 9 days during the LR2019 season October to February growing season (72 days) compared to the SR2018 season (63 days). On the other hand, SR2019 recorded fast crop development by recording averagely fewer days (62 days) to 50% flowering compared to LR2020 (74 days).

Across the four seasons, treatments under *Zai* system generally recorded fewer days to 50% flowering compared to the treatments under conventional system. In SR2018, conventional with sole manure treatment recorded 64 days to 50% flowering and this was 3.17% longer than the 62 days recorded in *Zai* with sole manure treatment in the same season (Table 4.10). The difference was however not significant at $p \leq 0.05$. In LR2019, *Zai* with sole mineral fertilizer recorded fewer days (70 days) to 50% flowering which was 4.2% shorter compared to similar treatment under conventional system (CF60) which recorded 73 days to 50% flowering.

In SR2019, *Zai* with manure and half rate mineral fertilizer recorded fewer days (71 days) to 50% flowering compared to conventional treatment with manure and half rate mineral fertilizer (74 days). Days to 50% flowering across the four seasons were also observed to generally fewer in treatments with organic amendment either solely or combined with half rate inorganic fertilizer in both *Zai* and conventional systems (Table 4.10).

Table 4.10: Duration of Gadam sorghum growth from sowing to 50% flowering expressed in calendar days

Stage	**Treatment**	**Calendar days**			
		SR2018	**LR2019**	**SR2019**	**LR2020**
50% flowering	ZNO	63 ^{a}	71 ^{a}	62 ^{a}	73 ^{a}
	ZM60	62 ^{a}	71 ^{a}	60 ^{a}	72 ^{a}
	CM60	64 ^{a}	72 ^{a}	62 ^{a}	75 ^{a}
	CNO	64 ^{a}	74 ^{a}	63 ^{a}	76 ^{a}
	ZF60	62 ^{a}	70 ^{a}	63 ^{a}	74 ^{a}
	CF60	64 ^{a}	73 ^{a}	63 ^{a}	75 ^{a}
	ZM30F30	62 ^{a}	70 ^{a}	60 ^{a}	71 ^{a}
	CM30F30	63 ^{a}	71 ^{a}	61 ^{a}	74 ^{a}
	P value	0.25	0.51	0.60	0.53

ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+ 60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}).

4.2.1.3 Effect of treatments on days to physiological maturity after sowing

Significant difference ($p \leq 0.05$) among the different treatments in the number of days to physiological maturity was not observed during the four experimental seasons (Table 4.11). Days to physiological maturity of Gadam sorghum ranged from 112- 115 days and 115-118 days in the SR2018 and SR2019, respectively. These days were longer in long rains seasons with days LR2019 and LR2020 ranging from 124- 126 days and 126-129 days, respectively.

Seasonal effect revealed faster crop development by decreasing days to physiological maturity in the short rain seasons compared to the long rain seasons. Averagely, the crop took lesser days to mature (114 days and 116 days) during the SR2018 and SR2019 seasons, which was 9.7% and 9.1% lesser days compared to the LR2019 (125 days) and LR2020 (128 days), respectively (Table 4.11).

On the other hand, across the four study seasons, treatments under *Zai* system recoded fewer days to physiological maturity compared to treatments under conventional system. Though this difference was not significant at $p \leq 0.05$ (Table 4.11).

Table 4.11: Duration of Gadam sorghum growth from sowing to physiological maturity expressed in calendar days

Stage	**Treatment**	**Calendar days**			
		SR2018	**LR2019**	**SR2019**	**LR2020**
Maturity	ZNO	114^{a}	125^{a}	116^{a}	127^{a}
	ZM60	112^{a}	124^{a}	115^{a}	126^{a}
	CM60	115^{a}	126^{a}	117^{a}	128^{a}
	CNO	115^{a}	126^{a}	118^{a}	129^{a}
	ZF60	114^{a}	125^{a}	116^{a}	127^{a}
	CF60	115^{a}	126^{a}	117^{a}	129^{a}
	ZM30F30	112^{a}	124^{a}	115^{a}	126^{a}
	CM30F30	112^{a}	125^{a}	117^{a}	128^{a}
	P value	0.29	0.43	0.45	0.45

ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+ 60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}).

4.2.2 Effects on sorghum grain yield

Generally, higher grain and stover yields were recorded during the short rains' seasons (SR2018 and SR2019) as compared to the long rains' seasons (LR2019 and LR2020). Even though treatments under *Zai* system recorded higher grain yields in LR2019 and LR2020, the difference was not significant at $p=0.05$.

Plate 4.1: Sorghum plantation in the study's experimental site

Zai treatments recorded significantly ($p \leq 0.05$) higher grain yields during the SR2018, SR2019 and LR2019 seasons as compared to the treatments under the conventional system (Figure 4.2). In SR2018, *Zai* with no input, *Zai* with sole cattle manure, *Zai* with full rate mineral fertilizer and *Zai* with combined cattle manure and half rate mineral fertilizer recorded 33%, 25%, 42% and 28% significantly ($p \leq 0.05$) higher sorghum grain yield compared to conventional system with no input, conventional with sole cattle manure, conventional with full rate mineral fertilizer and conventional with cattle manure and half rate mineral fertilizer, respectively (Figure 4.2).

The highest grain yields (4.85 t ha^{-1}) in SR2019 were recorded under the *Zai* pit system combined with cattle manure and half rate mineral fertilizer and this was significantly ($p \leq 0.05$) higher than the similar treatment under conventional system. During the SR2019 season, *Zai* pit with combined cattle manure and mineral fertilizer, *Zai* with sole cattle manure, *Zai* with full rate mineral fertilizer and *Zai* with no input recorded 48%, 58%, 39% and 40% significantly ($p \leq 0.05$) higher yields than the similar treatments under conventional system (Figure 4.2). In the LR2019 and LR2020 seasons, all the treatments under *Zai* system recorded higher grain yield than their conventional counterpart treatments, with the highest (1.39 t ha^{-1}) grain yield recorded under *Zai* with sole cattle manure in LR2020 being 21% higher than that of conventional with sole cattle manure (Figure 4.2).

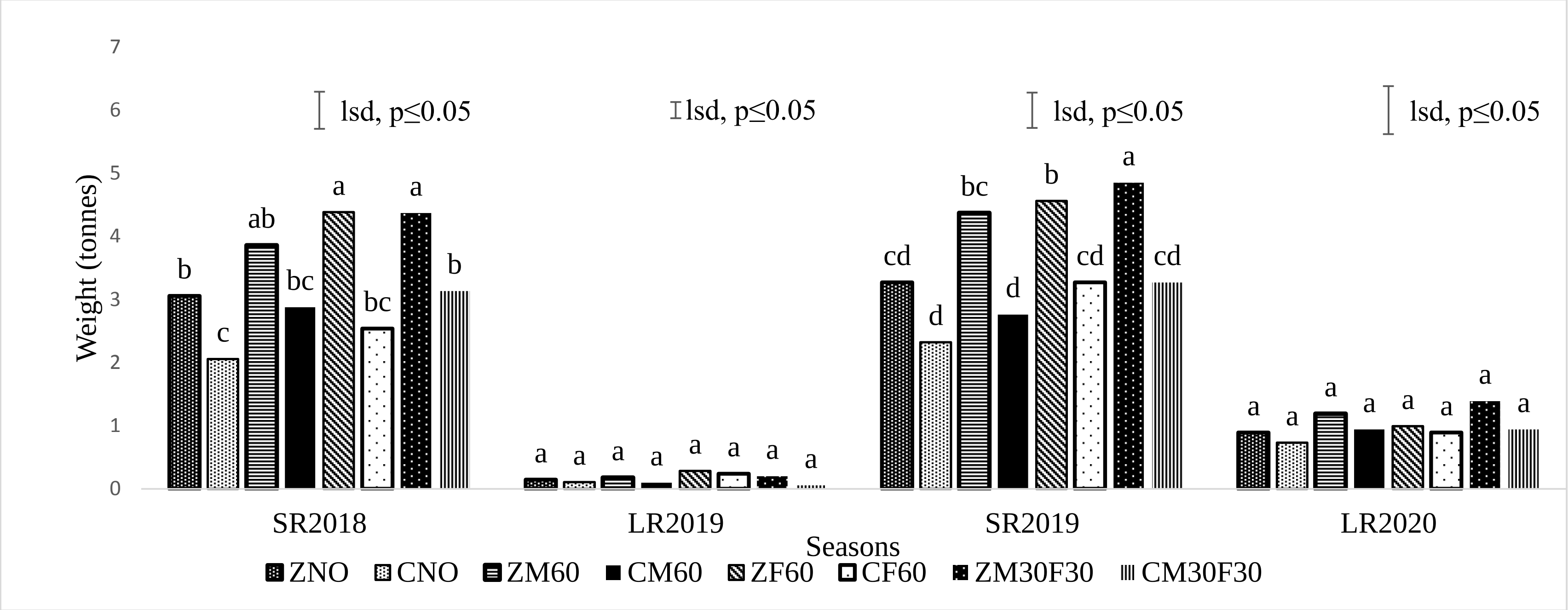


Figure 4.2: Sorghum grain yields (t ha^{-1}) during the 2018 short rains, 2019 long rains, 2019 short rains and 2020 long rains seasons at Kabati

(SR18= short rains 2018, LR19= long rains 2019, SR19= short rains 2019, LR20= long rains 2020, ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}). The Error bar denote the least significant difference (lsd) per season at $p \leq 0.05$. Different letters denote significant difference between treatments at $p \leq 0.05$ within each season.

4.2.3 Effect on sorghum stover yields

Highest stover yields were recorded during the SR2019 season while the lowest were recorded in the LR2019 season. In SR2018, *Zai* with cattle manure and half rate mineral fertilizer recorded 53% significantly ($p \leq 0.05$) higher stover yields than conventional with combined cattle manure and mineral fertilizer.

During the LR2019 season, *Zai* with no input, *Zai* with sole cattle manure, *Zai* with full rate mineral fertilizer and *Zai* with combined cattle manure and mineral fertilizer recorded 35%, 50%, 40% and 21% significantly ($p \leq 0.05$) higher stover yields compared to similar treatments under conventional system, respectively.

In SR2019 season, significantly ($p \leq 0.05$) higher stover yields were recorded under *Zai* treatments as compared to similar treatments under conventional system, with the highest (13.14 t ha^{-1}) under *Zai* with combined cattle manure and half rate mineral fertilizer being 35% higher than the similar treatment under conventional system (Figure 4.3).

Generally, across all the treatments in both systems in the four study seasons, treatments with fertility inputs recorded higher sorghum grain and stover yields as compared to both *Zai* and conventional systems without inputs. Furthermore, treatments with cattle manure application either solely or in combination with mineral fertilizer recorded significantly ($p \leq 0.05$) higher yields as compared to the treatments with sole mineral fertilizer application in both systems. All the treatments with sole cattle manure application or with combined manure and mineral fertilizer application recorded significantly higher yields as compared to *Zai* pit treatments without cattle manure application (Figure 4.3)

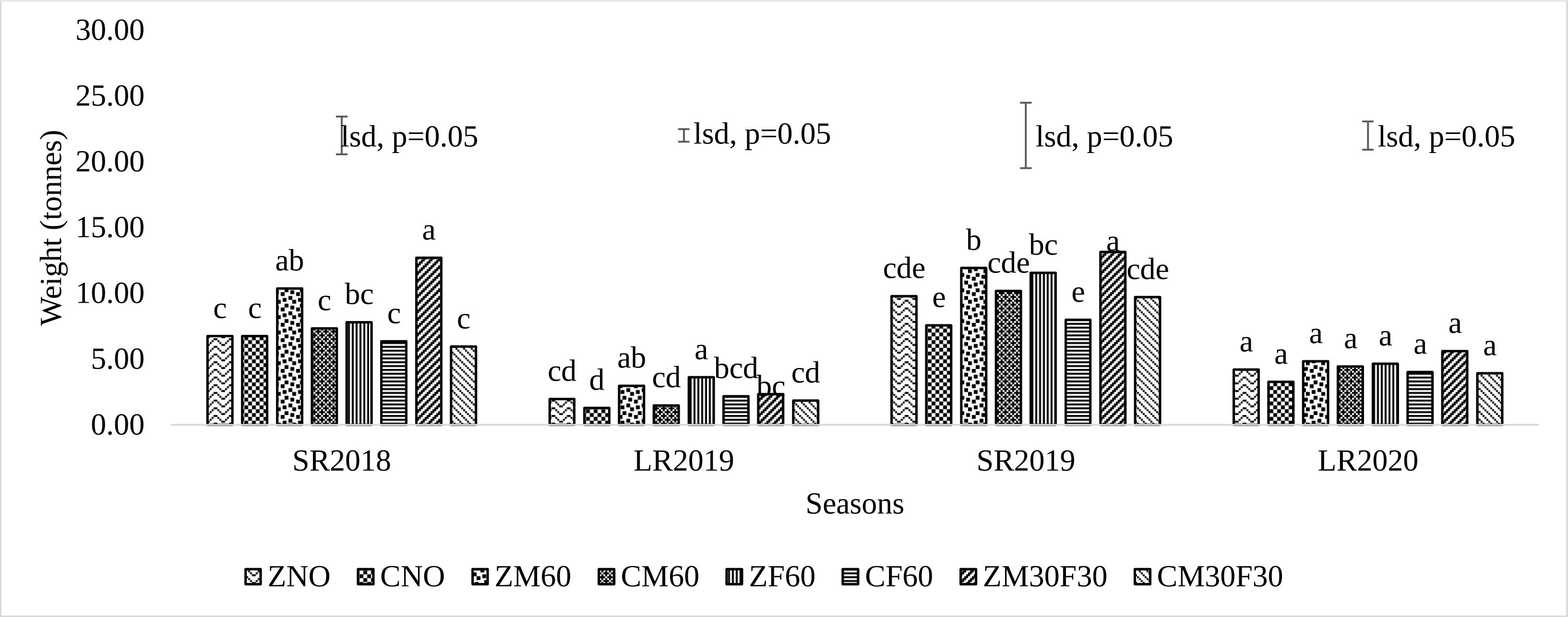


Figure 4.3: Sorghum stover yields (t ha^{-1}) during the 2018 short rains, 2019 long rains, 2019 short rains and 2020 long rains seasons at Kabati, Kitui County

(SR2018= short rains 2018, LR2019= long rains 2019, SR2019= short rains 2019, LR2020= long rains 2020, ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+ 60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}.). The Error bar denote the least significant difference (lsd) per season at p≤0.05. Different letters denote significant difference between treatments at p≤0.05 within each season.

4.3 Effects of *Zai* pit technology combined with selected ISFM amendment options on soil aggregate stability and moisture content

4.3.1 Treatment effects on aggregate stability

Generally, aggregate stability of soil particles was significantly higher ($p \leq 0.05$) in *Zai* treatments as opposed to similar treatments in the conventional system (Figure 4.4). The aggregate stability for the soils from *Zai* pit with manure combined with inorganic fertilizer recorded the highest significant ($p \leq 0.05$) mean weight diameter of 2.06mm followed by *Zai* with sole manure (2.01 mm). The mean weight diameter recorded in *Zai* with manure combined with chemical fertilizer was significantly higher ($p \leq 0.05$) by 35.43% than conventional approach with manure combined with mineral fertilizer which recorded a mean weight diameter of 1.44 mm (Figure 4.4).

Zai with sole manure recorded a mean weight diameter of 2.01 mm and this value was significantly higher by 25% than conventional with sole manure which recorded a mean weight diameter of 1.61mm (Figure 4.4). *Zai* pit with no input (1.78mm) and *Zai* with full rate mineral fertilizer (1.66mm) recorded mean weights diameters of 1.78 mm and 1.66 mm which were significantly high ($p \leq 0.05$) by 24% and 22% than the control and conventional with mineral fertilizer (Figure 4.4). Under *Zai* pit system, *Zai* with combined manure and half rate inorganic fertilizer had the highest mean weight diameter which was 2.5%, 15.7% and 24.1% higher than *Zai* with sole manure, *Zai* without input and *Zai* pit with exclusive inorganic fertilizer, respectively. In the conventional system, conventional with sole mineral fertilizer had the highest mean weight diameter of 1.61 mm which was 6.41%, 11.15% and 11.06% higher than conventional system with sole organic manure (1.51 mm), conventional system with combined manure and inorganic fertilizer (1.44 mm) and conventional system with no inputs (1.44 mm), respectively (Figure 4.4). Generally, all the treatments, except conventional system with sole mineral fertilizer, recorded a significantly higher mean weight diameter than the control (Figure 4.4). Mean weight diameter was significantly affected on by the planting system and input amendment at 0-15cm. The results indicate that *Zai* pit system significantly ($p \leq 0.05$) influenced soil aggregation in comparison with the conventional system (Figure 4.4).

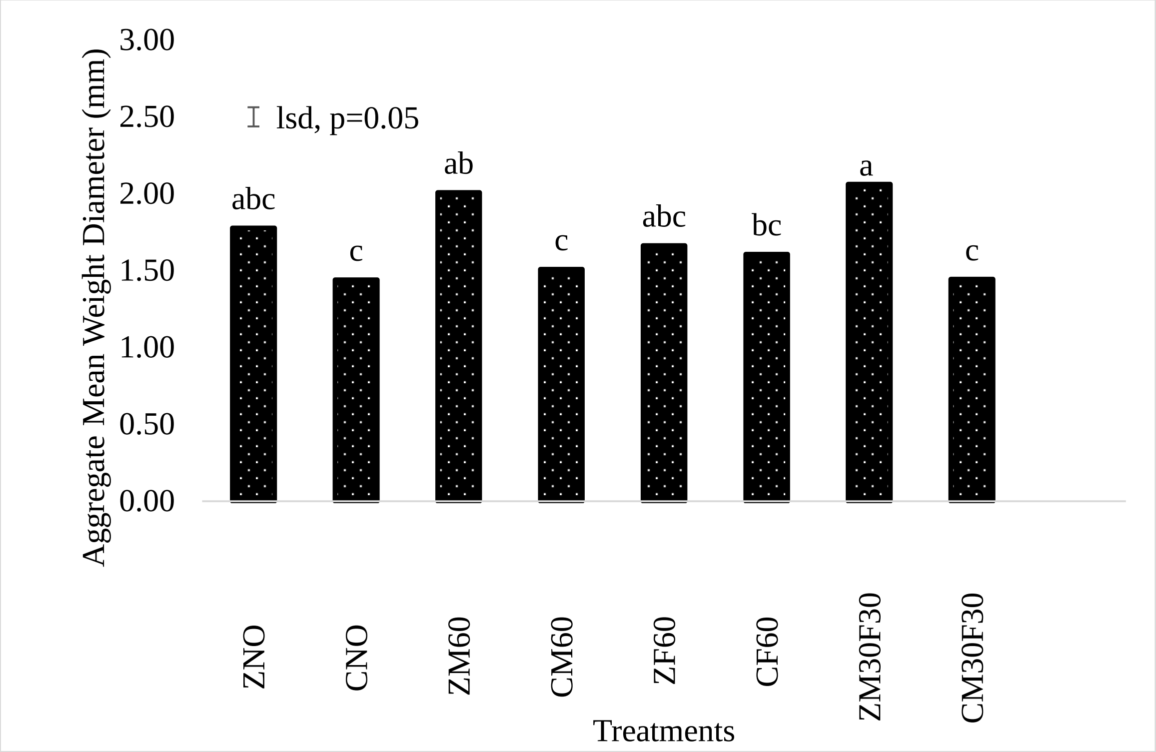


Figure 4.4: Treatment effects on soil aggregate stability (end of experiment) under *Zai* and conventional systems (0–15 cm)

(ZNO=Zai with no inputs, ZM60=Zai + sole manure, CM60= Conventional + sole manure, CNO= control, ZF60=Zai+ full rate chemical fertilizer (60 kg N ha^{-1}), CF60=Conventional + full rate chemical fertilizer (60 kg N ha^{-1}), ZM30F30=Zai+ manure+ half rate chemical fertilizer (30 kg N ha^{-1}), CM30F30=Conventional + Manure + half rate chemical fertilizer (30 kg N ha^{-1})). The Error bar denote the least significant difference (lsd) per season at $p \leq 0.05$. Different letters denote significant difference between treatments at $p \leq 0.05$.

4.3.2 Effects on soil moisture content

The determination of soil moisture content was done at different days (18, 32, 46, 60, 74, 88, 102 and 116) after sowing during the four study seasons. Generally, soil moisture content, which was expressed as volumetric water content (g cm^{-3}), recorded higher values during the SR seasons (SR2018 and SR2019) compared to the LR seasons (LR2019 and

LR2020). There was variability in the volumetric water content across the different days within the four study seasons, with low values being recorded towards the end of seasons. There was a variation in average soil moisture content among different treatments (Figures 4.5, 4.6, 4.7 and 4.8). A significant ($p \leq 0.05$) treatment influence was observed across the four seasons. All treatments in the *Zai* pit technology significantly influenced soil moisture content as opposed to comparable treatments under the conventional system across the different days in all the four seasons.

In the SR2018, cumulatively about 281.2 mm of rainfall was recorded in the first 32 days of the season (Figure 4.5) and soil moisture content increased concurrently in all experimental treatments during this period. Thereafter, soil moisture content decreased for all the treatments (Figure 4.5). During the whole season, the general trend was soil moisture content fluctuating in response to the rainfall patterns until end of the season. Treatment under *Zai* technology recorded significantly high soil moisture content values in contrast to similar treatments in the conventional system. In the same season, 18 days after sowing, with a cumulative rainfall of 53.9 mm and two previous non-rainy days, *Zai* pit with sole manure recorded the highest volumetric water content (2.51 g cm^{-3}), which was 23% significantly higher as opposed to conventional with sole manure treatment (Figure 4.5).
On the same day, among the treatments under conventional system, conventional with sole manure recorded a significantly ($p \leq 0.05$) highest volumetric water content value ($1.93 g/cm^3$) which was 18%, 25%, and 18% higher than the control, conventional with inorganic fertilizer and conventional with combined manure and chemical fertilizer. Generally, significantly higher volumetric water content values were observed in treatments under *Zai* technique with either absolute manure or combined manure and chemical fertilizer (Figure 4.5).

Across the four study seasons, lowest volumetric water content values were recorded during the LR2019 season. In this season, about 115.8 mm of precipitation fell in the first 32 days just after sowing leading to the concurrent rise in soil moisture content in experimental treatments both *Zai* and conventional systems (Figure 4.8). 18 days after sowing with cumulative rainfall of 57.2 mm and a 7-day dry-spell, all treatments, except conventional with sole mineral fertilizer recorded values higher than the control. On the same day, all the treatments under *Zai* pit farming approach recorded a significant ($p \leq 0.05$) treatment influence on volumetric water content compared to their counterpart treatments in the conventional system. 32 days after sowing with a cumulative rainfall of 115.8mm, *Zai* with sole manure recorded the highest volumetric water content (1.55 $g.cm^{-3}$) value which was significantly high ($p \leq 0.05$) by 58% than the volumetric water content value (0.98 $g.cm^{-3}$) recorded under conventional with exclusive cattle manure application treatment.

Conventional system with sole chemical fertilizer recorded the lowest soil moisture content. The longest dry period in this season occurred immediately after the 32nd day lasting up to the 100th day. Generally, treatments under *Zai* technology with cattle manure and those with combined manure and inorganic fertilizer had highest significant treatment effect on soil moisture contents (Figure 4.6).

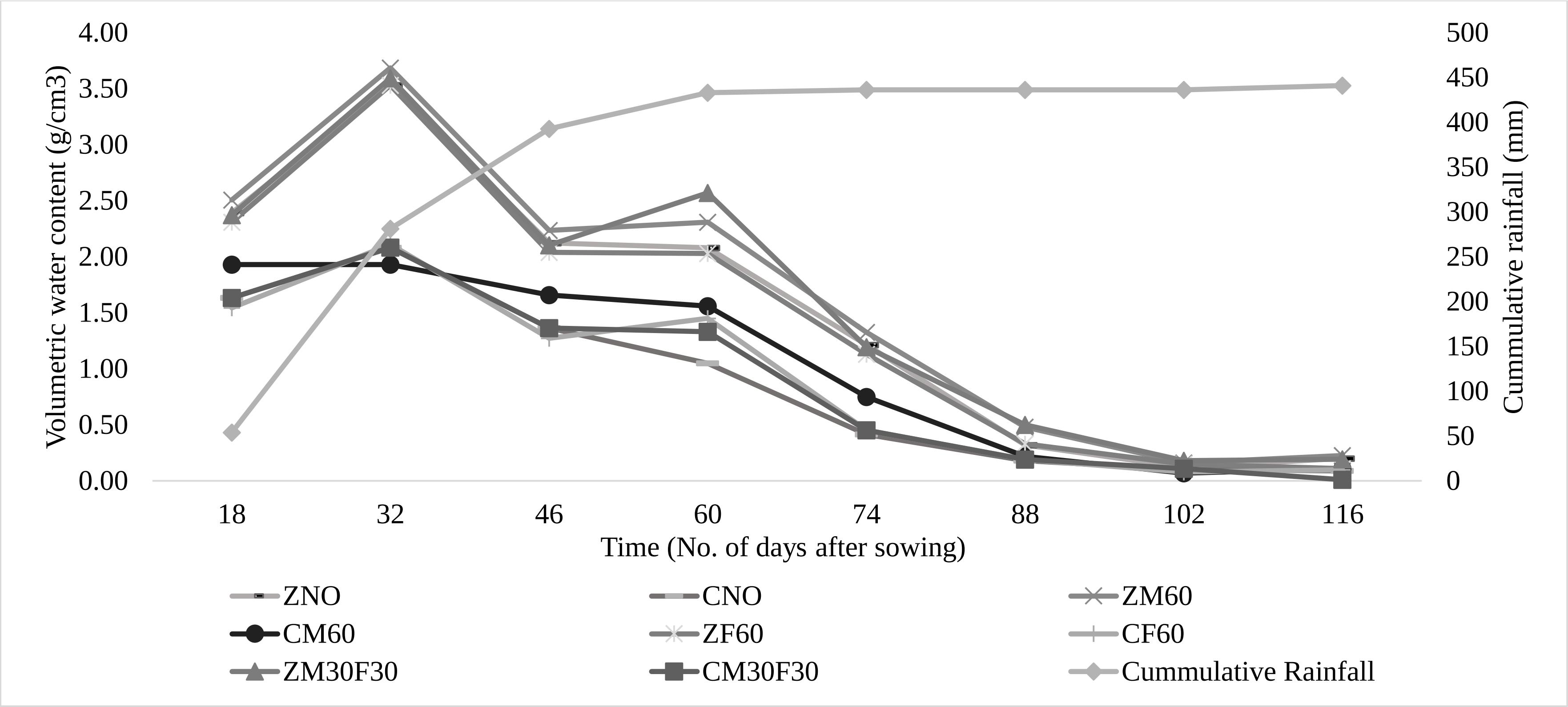


Figure 4.5: Soil moisture variations under different treatments at 0-15 cm soil profile during the SR2018 season in Kabati

(ZNO=Zai with no inputs, ZM60=Zai + sole manure, CM60= Conventional + sole manure, CNO= control, ZF60=Zai+ full rate chemical fertilizer (60 kg N ha^{-1}*), CF60=Conventional + full rate chemical fertilizer (60 kg N ha*$^{-1}$*), ZM30F30=Zai+ manure+ half rate chemical fertilizer (30 kg N ha*$^{-1}$*), CM30F30=Conventional + Manure + half rate chemical fertilizer (30 kg N ha*$^{-1}$*)).*

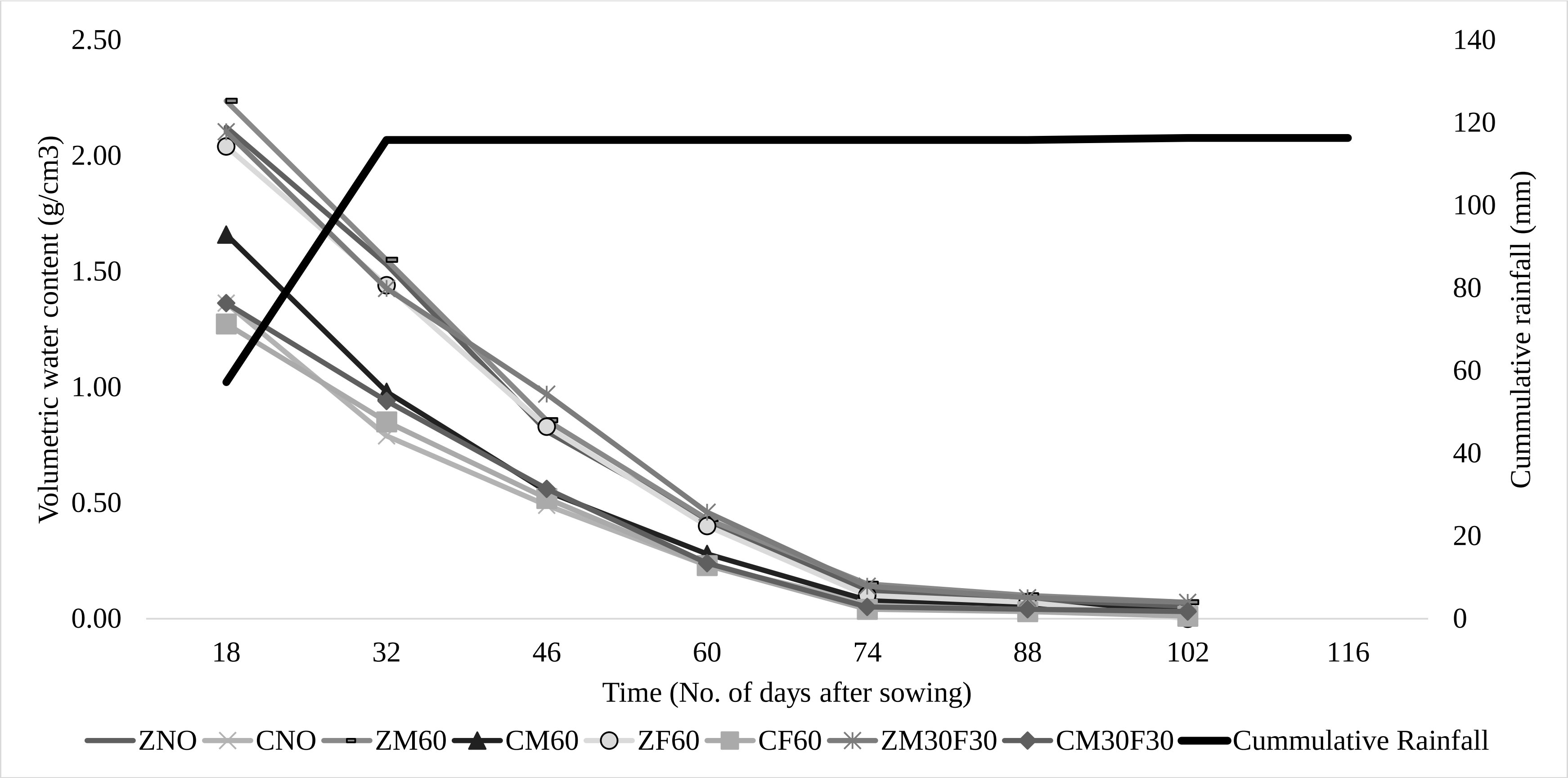


Figure 4.6: Soil moisture variations under different treatments at 0-15 cm soil profile during LR2019 season in Kabati

(ZNO=Zai with no inputs, ZM60=Zai + sole manure, CM60= Conventional + sole manure, CNO= control, ZF60=Zai+ full rate chemical fertilizer (60 kg N ha^{-1}*), CF60=Conventional + full rate chemical fertilizer (60 kg N ha*$^{-1}$*), ZM30F30=Zai+ manure+ half rate chemical fertilizer (30 kg N ha*$^{-1}$*), CM30F30=Conventional + Manure + half rate chemical fertilizer (30 kg N ha*$^{-1}$*)).*

The trend in SR2019 was similar to that observed in SR2018. Compared to the LR seasons, high rainfall amount was experienced (Figure 4.7) and soil moisture build up increased with increasing rainfall amounts during the initial days of the season. Soil moisture fluctuated concurrently in all treatments as influenced by rainfall. A significant ($p \leq 0.05$) treatment effect was observed in this season, with treatments under *Zai* system recording significantly ($p \leq 0.05$) higher treatment influence on volumetric water content as compared to their counterpart treatments under conventional system (Figure 4.7). 18 days after sowing, with a cumulative rainfall of 287.2 mm and two previous non-rainy days, *Zai* with sole manure recorded the highest (4.25 g.cm^{-3}) soil moisture content value while the lowest value was recorded under conventional with sole mineral fertilizer (2.23 g.cm^{-3}). *Zai* with sole manure, *Zai* pit with combined manure and chemical fertilizer, *Zai* with sole chemical fertilizer and *Zai* without input recorded 71%, 75%, 66% and 54% significantly higher ($p \leq 0.05$) soil moisture content values than similar treatments under conventional system, respectively (Figure 4.7).

In this season, 60 days after sowing, with a cumulative rainfall of 783.6 mm and being after an 18-day dry-spell, *Zai* with sole manure recorded the highest volumetric water content value (4.25 g.cm^{-3}) which was 44% (Figure 4.7) significantly higher as opposed to conventional treatment with sole manure (2.95 g.cm^{-3}). In the same season, 46 days after sowing, with accumulative rainfall of 610.6 mm and being after four non-rainy days, *Zai* pit with sole manure (4.12 g.cm^{-3}), *Zai* pit with no input (3.60 g.cm^{-3}), *Zai* pit with manure combined with mineral fertilizer (4.09 g.cm^{-3}) and *Zai* pit with sole mineral fertilizer (3.62 g.cm^{-3}) recorded significantly ($p \leq 0.05$) high volumetric water content values that were 94%, 58%, 78% and 71% higher than comparable treatments under conventional approach, respectively (Figure 4.7).

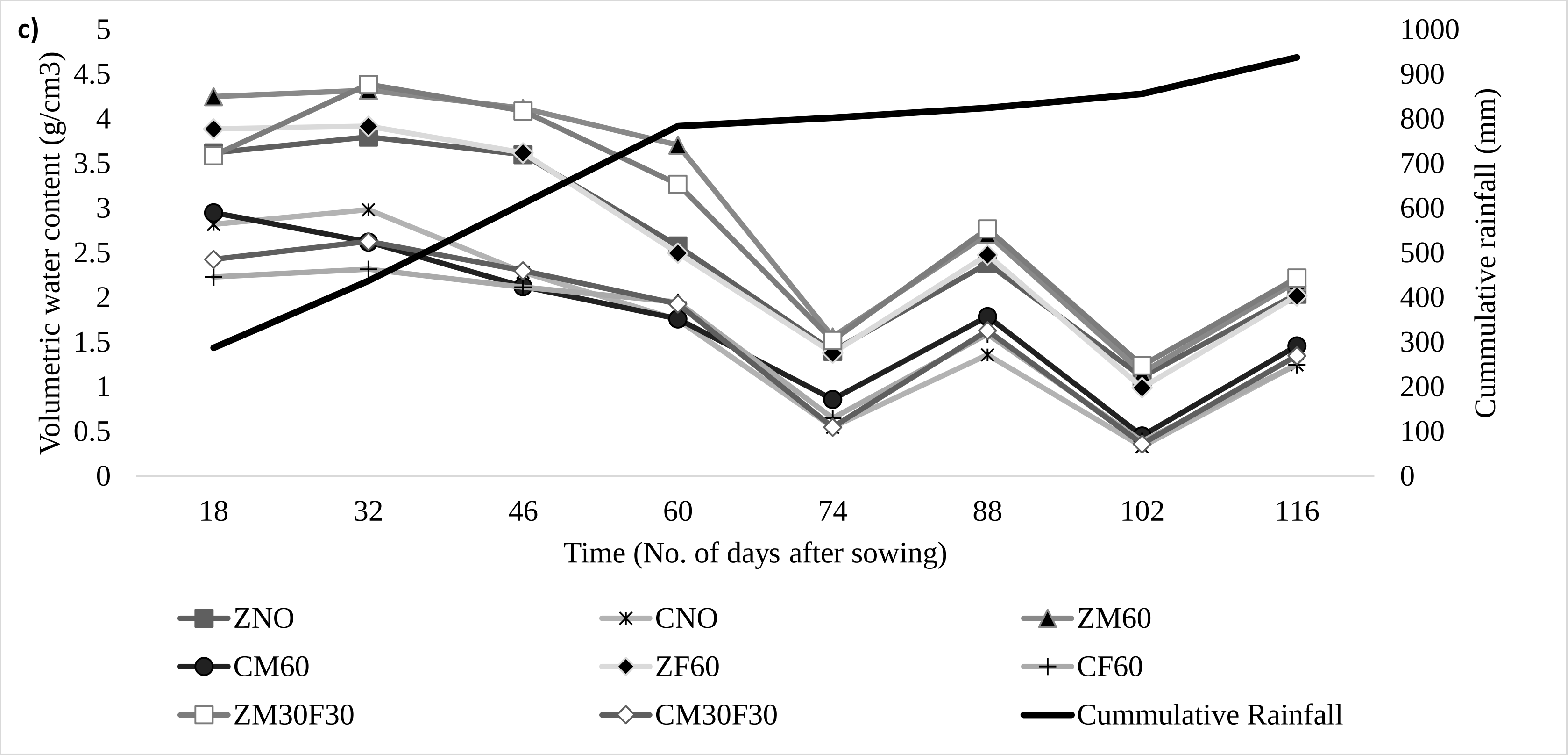


Figure 4.7: Soil moisture variations under different treatments at 0-15 cm soil profile during the SR2019 season in Kabati

(ZNO=Zai with no inputs, ZM60=Zai + sole manure, CM60= Conventional + sole manure, CNO= control, ZF60=Zai+ full rate chemical fertilizer (60 kg N ha^{-1}), CF60=Conventional + full rate chemical fertilizer (60 kg N ha^{-1}), ZM30F30=Zai+ manure+ half rate chemical fertilizer (30 kg N ha^{-1}), CM30F30=Conventional + Manure + half rate chemical fertilizer (30 kg N ha^{-1})).

The trend during the LR2020 season was similar to that observed in the LR2019 season. Both seasons had a distinct extremely prolonged within-season dry spell. The LR2020 dry-spell commenced 33 days after sowing and continued to the 103rd day. Soil moisture decreased in all treatments progressively into the season, though in the conventional system treatments, the reduction happened much earlier and at a quicker rate than in the *Zai* pit system treatments (Figure 4.8). Generally, in this season, treatments under *Zai* approach had significantly ($p \leq 0.05$) higher treatment effects on soil moisture levels in comparison to similar treatments under conventional farming approach (Figure 4.8). Eighteen days after sowing with a cumulative rainfall of 38 mm, *Zai* with sole manure recorded the highest (3.38 $g.cm^{-3}$) volumetric water content value which was 10% higher than the value recorded in similar treatment under conventional treatment.

On the same day, lowest (2.73 $g.cm^{-3}$) Volumetric water content value was recorded under conventional with no input. On the 46th day after sowing, with a cumulative rainfall of 225 mm and being after a 13-day dry-spell, *Zai* with manure combined with mineral fertilizer recorded the highest volumetric water content value (2.53 $g.cm^{-3}$) which was 55% higher than the value recorded under conventional with manure combined with mineral fertilizer treatment ((Figure 4.8). In the same season, under the conventional system, significantly ($p \leq 0.05$) higher volumetric water content values were recorded under treatments with exclusive cattle manure or combined manure with chemical fertilizer across the different days (Figure 4.8).

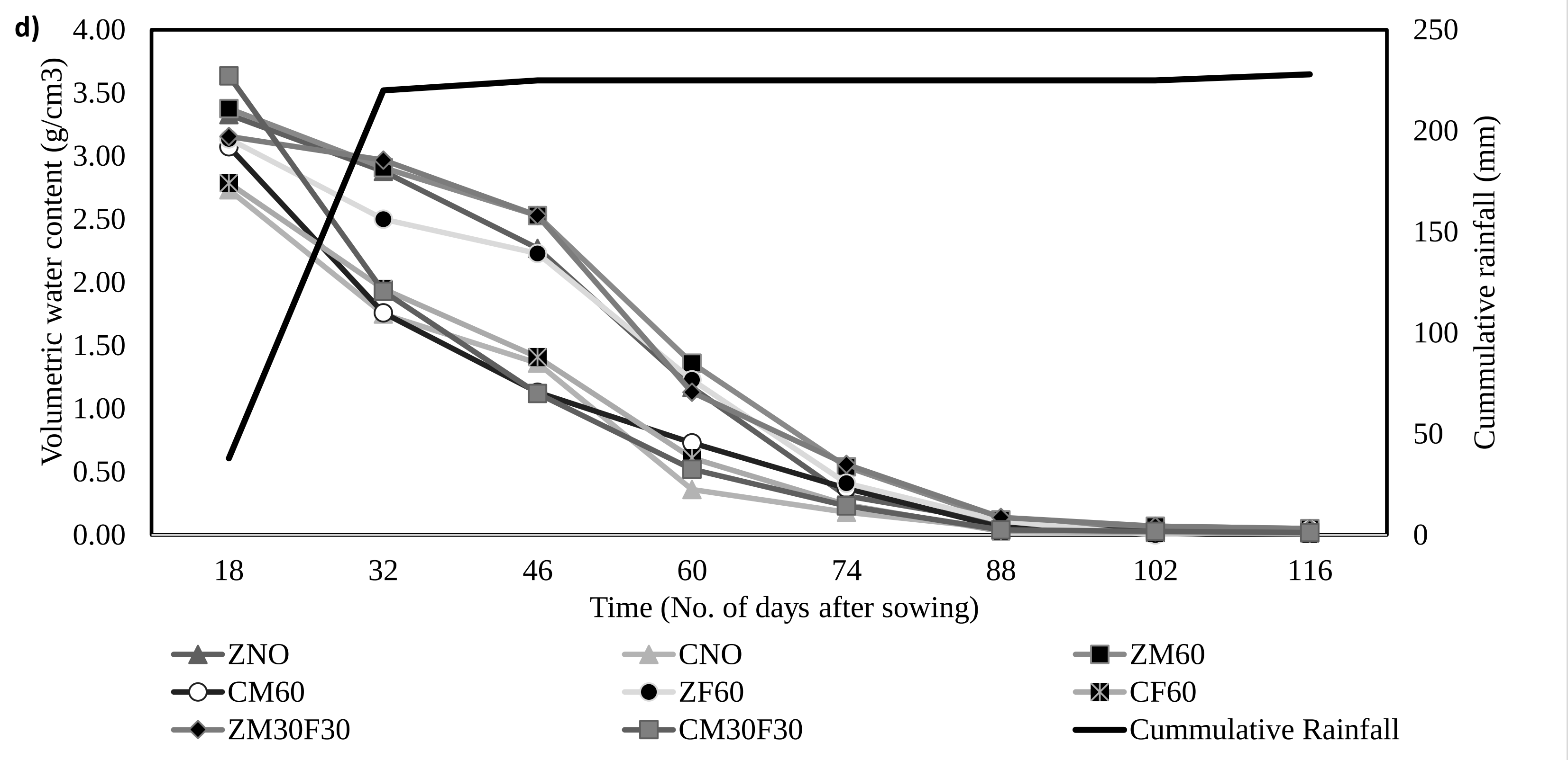


Figure 4.8: Soil moisture variations under different treatments at 0-15 cm soil profile during the LR2020 season in Kabati

(ZNO=Zai with no inputs, ZM60=Zai + sole manure, CM60= Conventional + sole manure, CNO= control, ZF60=Zai+ full rate chemical fertilizer (60 kg N ha^{-1}*), CF60=Conventional + full rate chemical fertilizer (60 kg N ha*$^{-1}$*), ZM30F30=Zai+ manure+ half rate chemical fertilizer (30 kg N ha*$^{-1}$*), CM30F30=Conventional + Manure + half rate chemical fertilizer (30 kg N ha*$^{-1}$*)).*

In the 0-15cm soil depth, all the four study seasons were characterized by alternating wetness (water accumulation periods) and dry spells (water depletion periods). During the four experimental seasons most of the rain fell in the first quarter of the seasons, with dry spells dominating the rest of the seasons (Figures 4.5, 4.6, 4.7 and 4.8). The influence of rainfall increased soil moisture content during the wet period early in the seasons. Treatments under *Zai* pit system recorded significantly ($p \leq 0.05$) higher volumetric water content values as opposed to values recorded in alike treatments under conventional system across different days in all the four seasons (Figures 4.5, 4.6, 4.7 and 4.8). Higher values were recorded in treatments with absolute manure and those with organic manure combined with chemical fertilizer under both systems. These results clearly indicate that the interaction between *Zai* pit system and the selected input amendments had significant treatment effect on soil moisture content compared to conventional planting system.

4.4 Effects of *Zai* pit technology combined with selected ISFM amendment options on total soil organic carbon and its selected labile organic fractions

4.4.1 Total organic carbon (TOC)

At the end of the experiment, higher total organic carbon amounts were recorded in treatments amended with organic inputs either solely or in combination with mineral fertilizer (Table 4.12). The treatment effect on soil organic carbon was highest (22.2 g.kg^{-1}) in conventional with manure and mineral fertilizer and this was 32% higher than *Zai* with manure and mineral fertilizer (16 g.kg^{-1}). *Zai* with sole manure application recorded 12% higher total organic carbon content (19.1 g.kg^{-1}) than conventional with sole manure (16.9 g.kg^{-1}). Conventional with sole mineral fertilizer (15.5 g.kg^{-1}) and conventional with no input (16.5 g.kg^{-1}) recorded 3% and 5% higher total organic carbon contents than *Zai* with sole mineral fertilizer and *Zai* with no input, respectively (Table 4.12). Among the *Zai* treatments, *Zai* with sole manure amendment recorded the highest total organic carbon content which was 20%, 23% and 18% higher than, *Zai* with no input, *Zai* with sole mineral fertilizer and *Zai* with manure and mineral fertilizer, respectively (Table 4.12).

Conventional with manure and mineral fertilizer recorded the highest (22.2 g.kg^{-1}) total organic content among the treatments under conventional system and this was 29%, 36% and 27% higher than conventional with no input, conventional with sole mineral fertilizer and conventional with sole manure, respectively (Table 4.12). Generally, under both systems, treatments with organic inputs, either solely or combined with mineral fertilizer recorded higher total organic carbon contents compared to the other treatments. However, despite the variation in total organic carbon contents between treatments in the two systems, the difference was not statistically significant at $p \leq 0.05$.

Table 4.12:Total organic carbon (g.kg-1) at the end of 2020 long rains season at Kabati, Kitui County (0-15 cm)

Treatment	**TOC (g.kg^{-1})**
ZNO	15.7 ^{a}
CNO	16.5 ^{a}
ZM60	19.1^{a}
CM60	16.9 ^{a}
ZF60	15.1 ^{a}
CF60	15.5 ^{a}
ZM30F30	16.0 ^{a}
CM30F30	22.2 ^{a}
P-value	0.24

Means with different superscript letters in the same column denote significant difference between treatments at $p \leq 0.05$ *(*=significant at p≤0.05, LSD= Least significant difference, ZNO=Zai with no inputs, CNO= Conventional with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, ZF60=Zai+ 60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}, TOC=Total organic carbon).*

4.4.2 Particulate organic carbon (POC)

Generally, significantly ($p \leq 0.05$) higher particulate organic carbon concentration was recorded in treatments under *Zai* pit system as compared to those under conventional system (Figure 4.9). Additionally, the treatments with organic amendments either solely or in combination with mineral fertilizer recorded significantly higher particulate organic carbon content as compared to the treatments without organic inputs.

Zai with manure and mineral fertilizer recorded the highest particulate organic carbon value (6.05 $g.kg^{-1}$) which was 20% significantly ($p \leq 0.05$) higher than conventional with manure and mineral fertilizer which recorded a value of 4.94 $g.kg^{-1}$ (Figure 4.9). *Zai* with sole mineral fertilizer (4.75 $g.kg^{-1}$), *Zai* with sole manure (5.79 $g.kg^{-1}$) and *Zai* with no input (3.99 $g.kg^{-1}$) recorded 10%, 19% and 10% significantly ($p \leq 0.05$) higher particulate organic carbon values compared to conventional with sole mineral fertilizer, conventional with sole manure and conventional with no input, respectively (Figure 4.9).

Among the treatments under *Zai* pit system, the treatment influence on particulate organic carbon content was highest in *Zai* with manure and mineral fertilizer and this was 41%, 4% and 24% significantly ($p \leq 0.05$) higher than *Zai* with no input, *Zai* with sole manure and *Zai* with sole mineral fertilizer, respectively (Figure 4.9).

Conventional with manure and mineral fertilizer (4.94 $g.kg^{-1}$) had the greatest influence on particulate organic carbon content among all the treatments under the conventional system and this was 31%, 3% and 14% higher than conventional with no input (3.99 $g.kg^{-1}$), conventional with sole manure (4.79 $g.kg^{-1}$) and conventional with sole mineral fertilizer (4.31 $g.kg^{-1}$), respectively (Figure 4.9). Generally, in both systems, the lowest particulate organic carbon contents were recorded in treatments with no input. All the treatments in both systems recorded higher particulate organic carbon contents than the control (Figure 4.9).

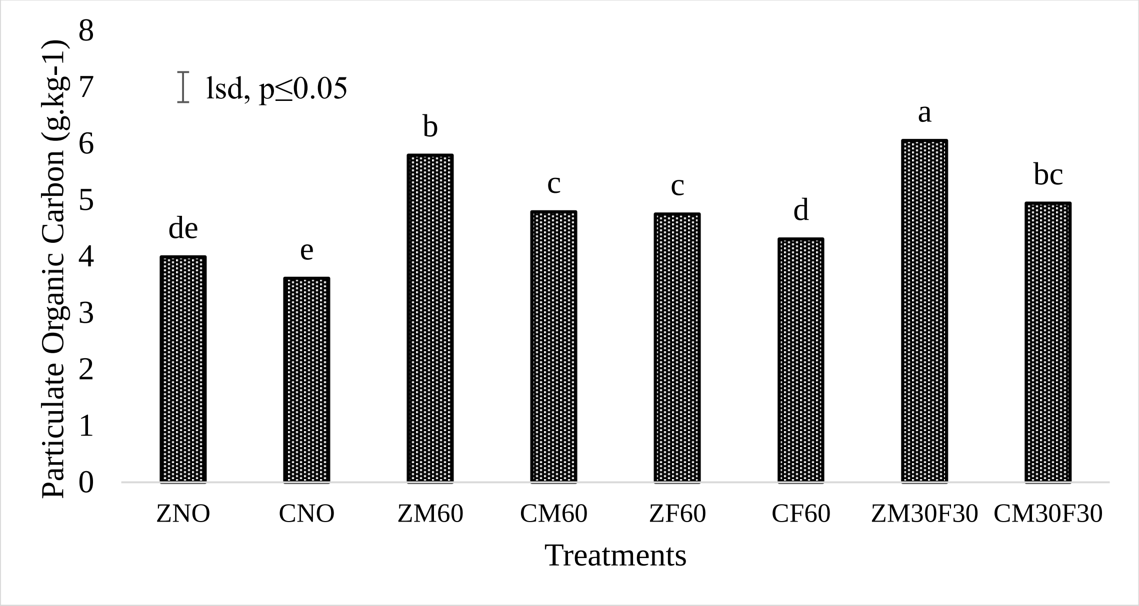


Figure 4.9: Particulate organic carbon (g.kg-1) at the end of 2020 long rains season (0-15 cm) at Kabati, Kitui County.

(ZNO=Zai with no inputs, ZM60=Zai + sole manure, CM60= Conventional + sole manure, CNO= control, ZF60=Zai+ full rate chemical fertilizer (60 kg N ha^{-1}*), CF60=Conventional + full rate chemical fertilizer (60 kg N* ha^{-1}*), ZM30F30=Zai+ manure+ half rate chemical fertilizer (30 kg N* ha^{-1}*), CM30F30=Conventional + Manure + half rate chemical fertilizer (30 kg N* ha^{-1}*)). The Error bar denote the least significant difference (lsd) per season at* $p \leq 0.05$*. Different letters denote significant difference between treatments at* $p \leq 0.05$*.*

4.4.3 Permanganate oxidizable carbon ($KMnO_4$-C)

Zai with manure and mineral fertilizer had the highest (3.69 $g.kg^{-1}$) significant ($p \leq 0.05$) influence on permanganate oxidizable carbon which was 12% higher than the amount recorded under conventional with manure and mineral fertilizer (3.26 $g.kg^{-1}$). Generally, all treatments under *Zai* system recorded significantly ($p \leq 0.05$) higher Permanganate oxidizable carbon amounts compared to their counterpart treatments under conventional treatments (Table 4.13).

Zai with no input (2.23 g.kg^{-1}), *Zai* with sole manure (3.66 g.kg^{-1}) and *Zai* with sole fertilizer (2.98 g.kg^{-1}) recorded 20%, 14% and 19% higher Permanganate oxidizable carbon amounts than conventional with no input, conventional with sole manure and conventional with sole fertilizer, respectively (Table 4.13). *Zai* with manure and mineral fertilizer recorded the highest (3.69 g.kg^{-1}) significant ($p \leq 0.05$) permanganate oxidizable carbon content among the treatments under *Zai* system. This value was 49%, 1% and 21% higher than *Zai* with no input, *Zai* with sole manure and *Zai* with sole mineral fertilizer, respectively (Table 4.13).

Among the treatments under conventional system, conventional with manure and mineral fertilizer recorded the highest (3.26 g.kg^{-1}) significant ($p \leq 0.05$) permanganate oxidizable carbon content which was 57%, 2% and 28% higher than conventional with no input (1.82 g.kg^{-1}), conventional with sole manure (3.19 g.kg^{-1}) and conventional with sole mineral fertilizer (2.47 g.kg^{-1}), respectively (Table 4.13).

This trend was similar to that seen in particulate organic carbon with higher permanganate oxidizable carbon contents being recorded in treatments under *Zai* system as compared to conventional system and also in treatments with organic amendments either solely or in combination with inorganic inputs (Table 4.13).

Table 4.13: Permanganate oxidizable carbon (g.kg^{-1}) at the end of 2020 long rains season at Kabati, Kitui County (0-15 cm)

Treatment	$KMnO_4$-C (g.kg^{-1})
ZNO	2.23^{d}
CNO	1.82^{e}
ZM60	3.66^{a}
CM60	3.19^{bc}
ZF60	2.98^{c}
CF60	2.47^{d}
ZM30F30	3.69^{a}
CM30F30	3.26^{b}
LSD	3.004
P-value	<0.05*

Means with same superscript letters in the same column denote no significant difference between treatments at $p \leq 0.05$ *(*=significant at $p \leq 0.05$, LSD= Least significant differences between means, ZNO=Zai with no inputs, CNO= Conventional with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, ZF60=Zai+ 60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}, $KMnO_4$-C= Permanganate oxidizable carbon).*

4.4.4 Light Fraction Organic Carbon (LFOC)

The trend in light fraction organic carbon values among treatments was generally similar to that observed in the other carbon fractions with higher values being recorded in treatments under *Zai* pit system and those with organic inputs either solely or in combination with inorganic inputs (Figure 4.10). The highest light fraction organic carbon value was recorded in *Zai* with sole manure (2.51 g.kg^{-1}) while the lowest in the control (1.47 g.kg^{-1}).

The value recorded in *Zai* with sole manure was 28% significantly ($p \leq 0.05$) higher than that recorded in conventional with sole manure (1.89 $g.kg^{-1}$) treatment. *Zai* with sole mineral fertilizer (1.73 $g.kg^{-1}$), *Zai* with manure and mineral fertilizer (2.25 $g.kg^{-1}$) and *Zai* with no input (1.69 $g.kg^{-1}$) recorded 4%, 15% and 14% significantly ($p \leq 0.05$) higher light fraction organic carbon values than values under conventional with sole mineral fertilizer (1.66 $g.kg^{-1}$), conventional with manure and mineral fertilizer (1.93 $g.kg^{-1}$) and conventional with no input (1.47 $g.kg^{-1}$), respectively (Figure 4.10).

On the other hand, under the conventional system, conventional with manure and mineral fertilizer recorded the highest light fraction organic carbon content which was 27%, 2% and 15% significantly higher than conventional with no input, conventional with sole manure and conventional with sole mineral fertilizer, respectively (Figure 4.10).

Zai with sole manure had the highest (2.51 $g.kg^{-1}$) significant ($p \leq 0.05$) treatment effect on light fraction organic carbon among the treatments under *Zai* pit system and this value was 39%, 37% and 11% significantly ($p \leq 0.05$) higher than *Zai* with no input (1.69 $g.kg^{-1}$), *Zai* with sole mineral fertilizer (1.73 $g.kg^{-1}$) and *Zai* with manure and mineral fertilizer (2.25 $g.kg^{-1}$), respectively (Figure 4.10). From the results, it is clear that *Zai* system combined with organic amendments had the greatest treatment effect on light fraction organic carbon.

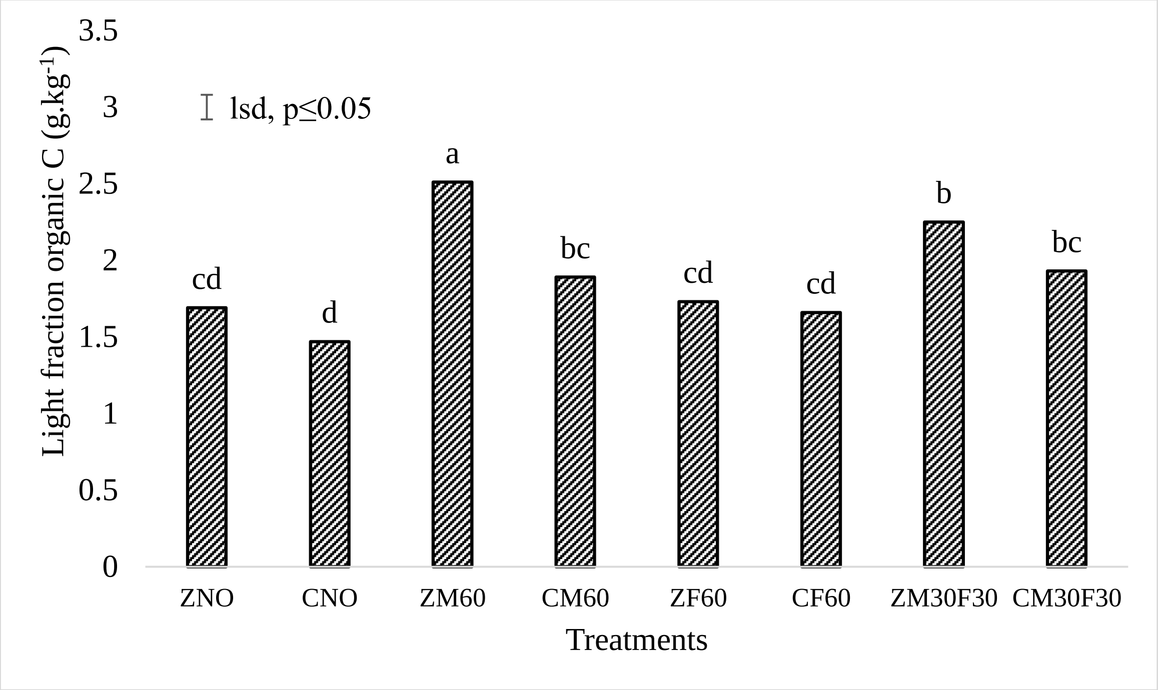


Figure 4.10: Light fraction organic carbon (g.kg-1) at the end of 2020 long rains season ((0-15 cm) at Kabati, Kitui County.

(ZNO=Zai with no inputs, ZM60=Zai + sole manure, CM60= Conventional + sole manure, CNO= control, ZF60=Zai+ full rate chemical fertilizer (60 kg N ha^{-1}), CF60=Conventional + full rate chemical fertilizer (60 kg N ha^{-1}), ZM30F30=Zai+ manure+ half rate chemical fertilizer (30 kg N ha^{-1}), CM30F30=Conventional + Manure + half rate chemical fertilizer (30 kg N ha^{-1})). The Error bar denote the least significant difference (lsd) per season at p≤0.05. Different letters denote significant difference between treatments at p≤0.05.

4.4.5 Dissolved organic carbon (DOC)

The treatment influence on dissolved organic carbon was significantly ($p \leq 0.05$) highest (125 mg.kg^{-1}) in *Zai* with sole manure and this was 33% higher than conventional with sole Manure treatment (90 mg.kg^{-1}). *Zai* with manure and mineral fertilizer recorded a significantly ($p \leq 0.05$) higher dissolved organic carbon content value (98 mg.kg^{-1}) which was 18% higher than the value recorded in similar treatment under conventional (82 $mg.kg^{-1}$) system (Table 4.14).

Zai with sole fertilizer and *Zai* with no input recorded 68 mg/kg and 45 $mg.kg^{-1}$ dissolved organic carbon contents and these were 9.2% and 9.3% significantly ($p \leq 0.05$) higher compared to their counterpart treatments under conventional system (Table 4.14). Among the treatments under the conventional system, conventional with sole manure had the highest influence on dissolved organic carbon and this was 9%, 37% and 75% higher than conventional with manure and mineral fertilizer, conventional with sole mineral fertilizer and conventional with no input, respectively (Table 4.14).

Among the *Zai* treatments, *Zai* with sole manure also recorded 94%, 59% and 24% significantly ($p \leq 0.05$) high dissolved organic carbon contents than *Zai* with no input, *Zai* with sole mineral fertilizer and *Zai* with manure and mineral fertilizer. The trend in dissolved organic carbon contents among treatments was similar to that observed in the total organic carbon contents, with significantly ($p \leq 0.05$) high amounts being recorded under treatments with organic inputs either solely or in combination with mineral fertilizer (Table 4.14).

Additionally, significantly ($p \leq 0.05$) higher dissolved organic carbon amounts were recorded in treatments under *Zai* pit system as compared to those under conventional system, indicating that the *Zai* pit system had a positive influence on the dissolved organic carbon contents (Table 4.14).

Table 4.14: Dissolved organic carbon (g.kg-1) at the end of 2020 long rains season at Kabati, Kitui County (0-15 cm)

Treatment	DOC (mg.kg^{-1})
ZNO	45 ^{e}
CNO	41 ^{e}
ZM60	125 ^{a}
CM60	90 ^{bc}
ZF60	68 ^{d}
CF60	62 ^{d}
ZM30F30	98 ^{b}
CM30F30	82 ^{c}
LSD	0.158
P-value	<0.05*

Means with same superscript letters in the same column denote no significant difference between treatments at $p \leq 0.05$ *(*=significant at $p \leq 0.05$, LSD= Least significant differences between means, ZNO=Zai with no inputs, CNO= Conventional with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, ZF60=Zai+ 60 kg N ha^{-1}, CF60=Conventional+ 60 kg N ha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kg N ha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kg N ha^{-1}, DOC= Dissolved organic carbon).*

4.5 Effects of *Zai* pit technology combined with selected ISFM amendment options on soil microbial biomass (C&N)

4.5.1 Soil microbial biomass carbon (SMBC)

Generally, Microbial biomass Carbon was significantly higher ($p \leq 0.05$) in treatments under *Zai* technology as compared to similar treatments under conventional system (Figure 4.11). Microbial biomass carbon for the soils from *Zai* pit with sole manure recorded the highest significant ($p \leq 0.05$) Microbial biomass carbon value (508 mg.kg^{-1}) followed by *Zai* with manure and mineral fertilizer (481 mg.kg^{-1}). Microbial biomass carbon value obtained in *Zai* with sole manure was significantly ($p \leq 0.05$) higher by 17% than conventional with sole manure which recorded a microbial biomass carbon value of 428 mg.kg^{-1} (Figure 4.11). *Zai* with manure and mineral fertilizer recorded a microbial biomass carbon that was 26% significantly ($p \leq 0.05$) higher than conventional with manure and mineral fertilizer which recorded a microbial biomass carbon value of 372 mg.kg^{-1} (Figure 4.11). *Zai* pit with no input and *Zai* with sole mineral fertilizer recorded microbial biomass carbon values of 283 mg.kg^{-1} and 301 mg.kg^{-1}which were significantly ($p \leq 0.05$) higher by 32% and 21% than conventional with no input (205 mg.kg^{-1}) and conventional with sole mineral fertilizer (243 mg.kg^{-1}), respectively (Figure 4.11).

Under *Zai* pit system, *Zai* pit with sole manure had the highest significant ($p \leq 0,05$) microbial biomass carbon value which was 57%, 51% and 6% higher than *Zai* with no input, *Zai* with sole mineral fertilizer and *Zai* pit with manure and mineral fertilizer, respectively (Figure 4.11). Under conventional system, conventional with sole manure had the greatest influence on microbial biomass carbon recording a significantly ($p \leq 0.05$) high value which was 71%, 55% and 14% higher than conventional with no input (205 mg.kg^{-1}), conventional with sole mineral fertilizer (243 mg.kg^{-1}) and conventional with manure and mineral fertilizer (372 mg.kg^{-1}), respectively (Figure 4.11). Generally, all the treatments recorded a significantly ($p \leq 0.05$) higher microbial biomass carbon values than the control.

Soil microbial biomass carbon was significantly affected by the planting system and amendments application at 0-15 cm. The results indicate that *Zai* pit system significantly ($p \leq 0.05$) increased microbial biomass carbon compared to the conventional system (Figure 4.11). It is also evident from the results that organic amendment had a significant influence on microbial biomass carbon whether applied solely or in combination with inorganics.

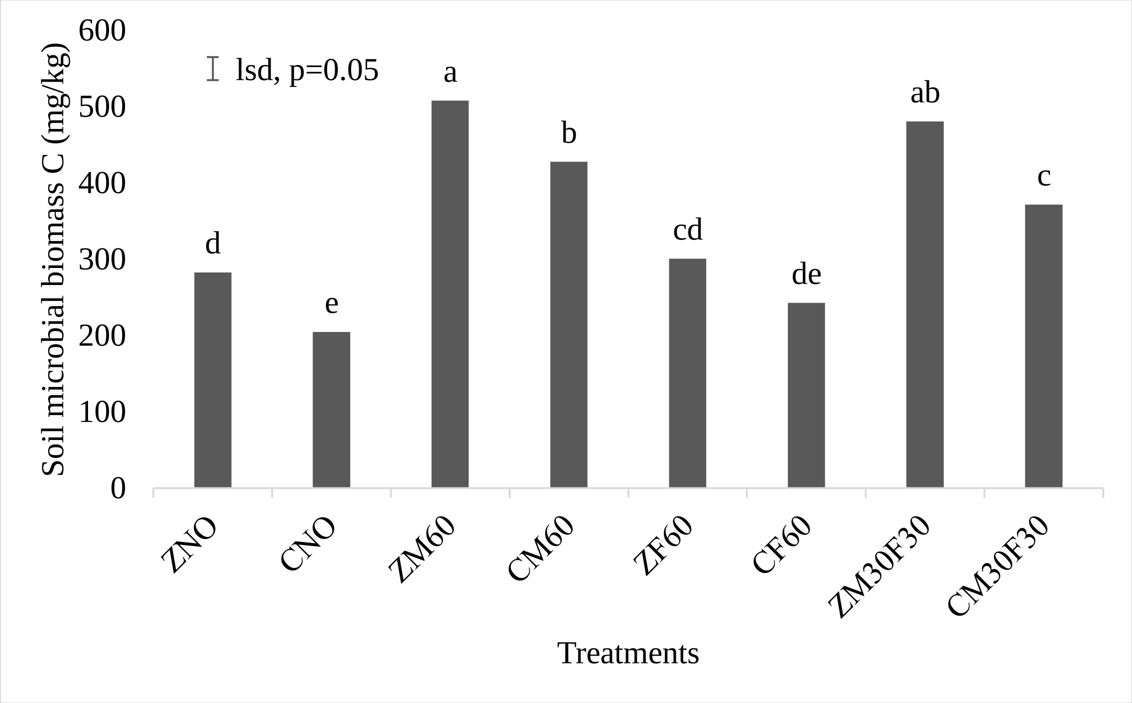


Figure 4.11: Soil microbial biomass carbon in different treatments at the end of the experiment.

(ZNO, Zai with no inputs; CNO, Conventional with no inputs; ZM60, Zai + Manure; CM60, Conventional + Manure; ZF60, Zai + 60 kg N ha^{-1}*; CF60, Conventional + 60 kg N ha*$^{-1}$*; ZM30F30, Zai + Cattle manure + 30 kg N ha*$^{-1}$*; CM30F30, Conventional + Cattle manure + 30 kg N ha*$^{-1}$*. The Error bar denote the least significant difference (lsd) per season at* $p \leq 0.05$*. Different letters denote significant difference between treatments at* $p \leq 0.05$*.*

4.5.2 Soil microbial biomass nitrogen (SMBN)

A significant ($p \leq 0.05$) difference in treatment effect was observed among treatments under the two systems with regards to their effect on microbial biomass nitrogen, with treatments under *Zai* pit system recording significantly ($p \leq 0.05$) higher microbial biomass nitrogen values as compared to their counterpart treatments under conventional system (Figure 4.12). *Zai* with sole manure recorded the highest (295 mg.kg^{-1}) microbial biomass nitrogen value while the lowest value was recorded in the control (108 mg.kg^{-1}). *Zai* with sole manure, *Zai* with manure and mineral fertilizer, *Zai* with sole mineral fertilizer and *Zai* with no input recorded 37%, 13%, 13% and 51% significantly ($p \leq 0.05$) higher microbial biomass nitrogen values than similar treatments under conventional system, respectively (Figure 4.12). Among the treatments under *Zai* system, *Zai* with sole manure recorded the highest value of microbial biomass nitrogen which was significantly ($p \leq 0.05$) higher than *Zai* with no input (181 $mg.kg^{-1}$), *Zai* with sole mineral fertilizer (191 $mg.kg^{-1}$) and *Zai* with manure and mineral fertilizer (240 $mg.kg^{-1}$) by 48%, 43% and 21% respectively (Figure 4.12).

Conventional with manure and mineral fertilizer recorded the highest microbial biomass nitrogen value (211 $mg.kg^{-1}$) among the treatments under conventional system and this was 65%, 3% and 23% significantly ($p \leq 0.05$) higher than conventional with no input (108 $mg.kg^{-1}$), conventional with sole manure (204 $mg.kg^{-1}$) and conventional with sole mineral fertilizer (168 $mg.kg^{-1}$). Generally, the trend among treatments under the two systems were similar to that observed under microbial biomass carbon, with high values being recorded in treatments under *Zai* systems compared to those under conventional system (Figure 4.12). Similarly, higher microbial biomass nitrogen values were recorded in treatments with organic amendments either solely or in combination with mineral fertilizer implying a positive effect of organic inputs on microbial biomass nitrogen (Figure 4.12).

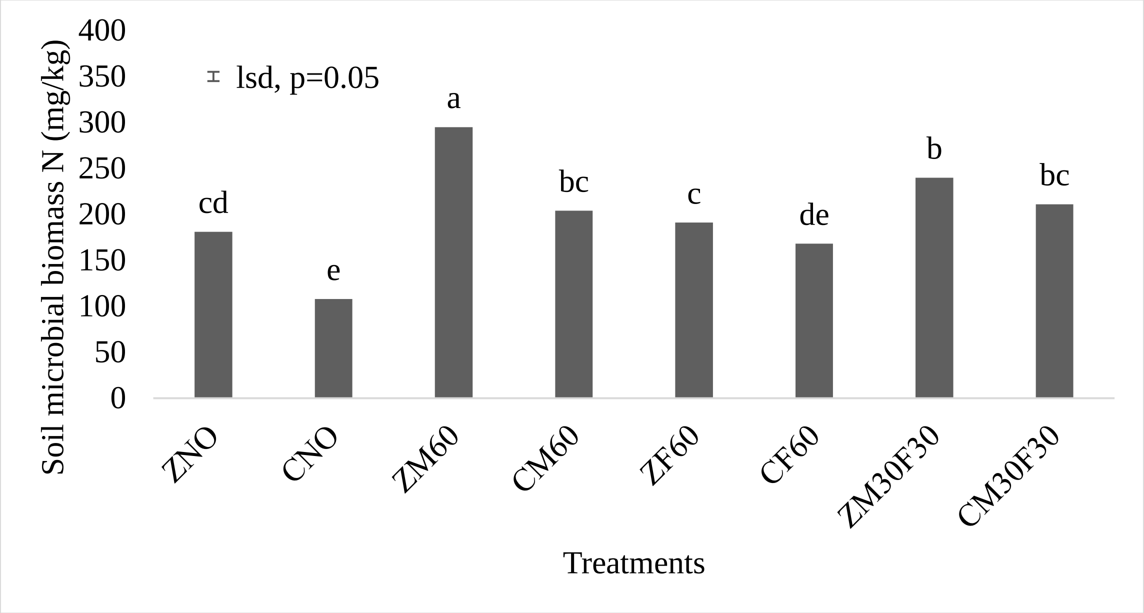


Figure 4.12: Soil microbial biomass nitrogen in different treatments at the end of the experiment

(ZNO, Zai with no inputs; CNO, Conventional with no inputs; ZM60, Zai + Manure; CM60, Conventional + Manure; ZF60, Zai + 60 kg N ha^{-1}*; CF60, Conventional + 60 kg N ha*$^{-1}$*; ZM30F30, Zai + Cattle manure + 30 k gN ha*$^{-1}$*; CM30F30, Conventional + Cattle manure + 30 kg N ha*$^{-1}$*. The Error bar denote the least significant difference (lsd) per season at* $p \leq 0.05$*. Different letters denote significant difference between treatments at* $p \leq 0.05$*.*

CHAPTER FIVE

5.0 DISCUSSION, CONCLUSIONS AND RECOMMEDATIONS

5.1 Effects of *Zai* pit technology combined with selected ISFM amendment options on selected soil chemical properties

5.1.1 Rainfall characteristics and distribution during the SR2018, LR2019, SR2019 and LR2020 experimental seasons

Precipitation quantities varied across the four growing seasons which demonstrated clearly distinguishable rainfall patterns. Higher rainfall amounts were recorded in the short rain seasons as compared to the long rain seasons. Additionally, rainy days number differed across the four seasons with the short rain seasons recording the most days while the long rain seasons recording the least number of rainy days.

Every year, precipitation in Eastern Kenya is separated into two contrasting seasons: long rains which occurs from March to May and short rains which prevail between October to December (Jaetzold *et al.,* 2007). Because short rains season receives the majority of the total annual rainfall, it is regarded as more reliable. In comparison to the long rain season, crop yields are higher during this season (Getare *et al.,* 2021; Jaetzold *et al.,* 2007). In this study, the short rains had the highest total season rainfall amounts, which positively influenced soil moisture in comparison to the long rain seasons.

Most of the rainfall fell during the first two months of the SR2018 and SR2019 seasons, with an extended drought spell commencing from the 64th day after sowing and lasting till end of the growing seasons. In contrast, during the first month of the long rain seasons, there were alternating periods of wet and dry days with extremely prolonged intra-seasonal dry spells as opposed to the drought episodes recorded in the short rain seasons. Similar to Usman and Reason (2004) and Barron *et al.* (2003), this study defined dry spell as a period of consecutive 5-10 dry days with a less than 5mm total amount of rainfall resulting in a soil water deficit causing crop water stress. According to Araya and Stroosnijder (2010), meteorological drought spells are major causes of low yield in many low rainfall-drought prone environments and in this study, the lowest yields were recorded during LR2019 and LR2020 seasons which experienced the longest dry spells.

Similar to Msongaleli *et al.* (2017) sowing was conditioned upon the previous day having received significant rainfall (minimum of 30 mm) so as to wet the soil, provided that no dry spell of 5 days or more occurred in the week after that date (Odekunle, 2006). This ensured sufficient soil moisture to support sorghum seed germination. The most vulnerable growth stages for any crop in dry spell occurrences are the germination and flowering (Gao *et al.,* 2019; Mugalavai *et al.,* 2012) which explains the near to complete crop failure experienced in the LR2019 season since the prolonged dry-spell (0mm of rainfall) which occurred from day 27 to day 100 after planting coincided with the flowering period. The higher crop yields in the other three seasons, as opposed to the LR2019 season, were as a result of dry-spell scenarios occurring long after flowering. The findings of a study by Msongaleli *et al.* (2017) revealed low sorghum yield experienced was as a result of low rainfall amounts and prolonged periods of dry spells during critical periods (flowering and seed development) that caused water stress.

Rainfall amount and distribution are very critical rainfall characteristics that has an impact on the agricultural productivity in rainfed regions (Subash *et al.,* 2012). The most important rainfall characteristics influencing agricultural production in rainfed systems are the date of onset of effective rainfall, dry spell durations, the time of occurrence of dry spell and number of rainy days (Satpute, 2018). In this study, all these factors contributed to the high yields experienced in the short rain seasons and the low crop yield recorded in the long rain seasons. According to Yazar and Ali (2016), low precipitation amounts coupled soil water stress and low nutrient availability have been found to limit crop productivity in arid and semiarid environments of the world.

According to Nyakudya and Stroosnijder (2011), low crop yields in arid and semi-arid regions are often experience due to low rainfall amounts with longer dry spell periods that causes water stress. The results of a study by Gbangou *et al.* (2020) demonstrates that high variability in seasonal rainfall and dry spell length and frequency risks rainfed crop systems especially during critical growing stages. According to Gbangou *et al.* (2020), one of the issues is the risk associated with crop failure during growing stages due to insufficient soil moisture. This can not only lead to a decrease in crop yield but also generate additional costs for replanting in case of failure in germination. Furthermore, droughts and dry spells commonly associated with rainfed agriculture in SSA (Ayanlade *et al.,* 2018), pose a risk to food security (Grafton *et al.,* 2015). Drought afflicted more than 13 million people in the Horn of Africa between 2008 and 2010, including 3.75 million Kenyans (Muller, 2014). The continuing climate change and variability will significantly impact on African rain-fed agriculture (Mukherjee *et al.,* 2018; Muller, 2014; IPCC, 2007) . According to Rosegrant *et al.* (2002), rainfed grain yields in underdeveloped nations average 1.5 t ha^{-1} as opposed to 6 t ha^{-1} (Rockström & Falkenmark, 2000) in areas with consistent rainfall and adequate fertilizer availability (Clarke *et al.,* 2017). The yield gap between what is harvested by farmers and what could be realized demonstrates the need for new farming production systems in Sub-Saharan Africa (Wani *et al.,* 2009).

5.1.2 Soil pH

Generally, there was variation in pH levels across the treatments with all treatments that had manure application whether solely or in combination with mineral fertilizer increasing while those with sole application of mineral fertilizer decreasing at the end of the experiment (Table 4.4).

The decrease in soil pH in mineral fertilizer-amended treatments could be as a result of the H^+ ions, which were added on the cation exchange complex of soils from the mineral fertilizer. Nitrogen fertilization acidifies the soil by the oxidation of dry-deposited compounds, loss of basic cations through ion exchange, and plant uptake and nitrification of ammonium (Cai *et al.,* 2019). Synthetic nitrogen application significantly reduces exchangeable base cations in soils, leading to low soil pH. A decline in base saturation is symptomatic of soil acidification (Stevens *et al.,* 2009). Additionally, synthetic nitrogen application shifts soils into the Al^{3+} buffering stage. Aluminium is released into solution at a pH below 5 by the hydrolysis of both Al-hydroxides and silicates on clay mineral surfaces (Cai *et al.,* 2019). Decrease in soil pH increases the availability of potentially toxic heavy metals and also contribute to the reduction of the microbial organisms beneficial in root functions (Stevens *et al.,* 2009).

The increase in soil pH in manure-amended soils could be attributed to the reduction of exchangeable aluminum in acidic soils (pH 4.5-5.5) which is considered to occur through aluminum precipitation or chelation on organic colloids (Mucheru-Muna *et al.,* 2007; Hue & Amien, 1989). This observation could also be attributed to the complexation of soluble aluminum by organic molecules, especially organic acids (Hue & Amien, 1989). Generally, the ash-alkalinity nature of manure is associated with protons to neutralize soil acidity (Rukshana *et al.,* 2014). The alkalinity of organic materials following the decarboxylation of organic anions and the ammonification of organic nitrogen (Cai *et al.,* 2019) are the major causes of the recorded increase in soil pH in manure-amended soils.

pH decreases in fertilizer amended soils corroborate with the findings by Cai *et al.* (2019) where lowered soil pH was recorded in treatments with sole application of N fertilizers which resulted in no yield after 12 years of study. Further, other studies reported that synthetic fertilizer application could significantly decrease soil pH (Zhu *et al.,* 2018; Cai *et al.,* 2015; Mucheru-Muna *et al.,* 2007). The increase in soil pH recorded in manure-amended soils correspond with the findings by Wildemeersch *et al.* (2015) where increment in soil pH to 5.0 from the initial 4.2 was recorded following manure application. A number of other studies have also reported significant increases in pH with manure treatment (Mucheru-Muna *et al.,* 2014, 2007; Mutegi *et al.,* 2012; Mugwe *et al.,* 2009; Bayu *et al.,* 2005; Eghball, 2002).

5.1.3 Electrical conductivity

Higher increases in electrical conductivity recorded in manure amended soils (Table 4.5) could be as a result of presence of dissolved salts in the cattle manure used as a result of feed additives which when mixed with water, they dissolve and break into tiny electrically charged ions, hence increasing the ability of the soil solution to conduct electricity. The increase could also be attributed to the resultant increases in exchangeable potassium ions and organic matter, which supplies a pool of nutrients and ions that can be released in the soil solution. This observation corresponds with the findings by Ozlu & Kumar (2018) who reported increased Electrical conductivity by 2.2 times in manure-amended soils as compared to that of fertilizer for 0-10 cm depth. The higher increase in electrical conductivity in the treatments with manure application as compared to non-manure amendments is consistent with the findings of several other studies (Zhu *et al.,* 2018; Miller *et al.,* 2017; Carmo *et al.,* 2016; Cai *et al.,* 2015; Zhao *et al.,* 2014; Eghball, 2002; Eigenberg *et al.,* 2002; Dong *et al.,* 2001).

5.1.4 Total Nitrogen

Generally, there was reduction in total nitrogen in all the treatments at the end of the experiment (Table 4.6). The observed decrease in total nitrogen could be attributed to uptake for utilization by sorghum plants. Furthermore, the reduction in total N recorded in manure-amended treatments could be as a result of increased microbial biomass which could utilize the nitrogen. Losses could have also occurred through leaching, denitrification and ammonia volatilization. These results correspond with the findings of other studies where reduction in total nitrogen were recorded and the losses attributed to erosion (Jaetzold *et al.,* 2007), utilization through microbial activity (van Diepeningen *et al.,* 2006) and losses through denitrification and ammonia volatilization (Ju *et al.,* 2009).

5.1.5 Total organic carbon

The recorded significant increases in total organic carbon in treatments with sole application of manure (Table 4.7) could be as a result of addition of more carbon source through manure application. Manure directly increases carbon inputs into the soil and also influences crop residues, which potentially sequestrates agricultural soil organic carbon and enhances nutrient release. These finding is corroborated by the finding by Hati *et al.* (2007) who attributed the observed increase in soil organic carbon among different fertility treatments after 28 years of study to the addition of carbon source through crop residues, root biomass and farmyard manure. Similarly, other studies have reported a significant increase in soil organic carbon in treatments that had sole cattle manure application (Bedada *et al.,* 2014; Dunjana *et al.,* 2012) and in those with manure and half rate fertilizer (Bedada *et al.,* 2014; Kaur *et al.,* 2008). Several other studies have reported increases in organic carbon content in soil as a result of manure application compared to the addition of mineral fertilizer (Xin *et al.,* 2016; Zhou *et al.,* 2016; Kuzyakov & Blagodatskaya, 2015; Dunjana *et al.,* 2012; Liang *et al.,* 2012; Bandyopadhyay *et al.*, 2010; Lal, 2008; Mucheru-Muna *et al.,* 2007).

5.1.6 Extractable phosphorous

There were increases in extractable phosphorous in all the treatments at the end of the experiment (Table 4.8). The higher levels of phosphorous recorded in treatments with sole fertilizer or fertilizer combined with manure application was as a result of phosphorous available in the NPK fertilizer used. *Zai* treatments with either sole cattle manure application or manure combined with mineral fertilizer had higher extractable phosphorous levels at the end of the experiment as compared to similar treatments under conventional system. This could be as a result of the composition of cattle manure, which contains both organic and inorganic phosphorous. Plants take up phosphorous in form of inorganic orthophosphates and it generally constitutes 45% to 90% of the phosphorous in manure (Coonan *et al.,* 2019), making manure an important source of phosphorous. Despite the effect of nutrient amendment inputs, all the treatments under *Zai* system recorded higher phosphorous levels as compared to conventional treatments. This could be due to the ability of the *Zai* pit system to hold nutrients in place. The pits also retained more water which enhanced decomposition by microbial organisms. The current trend of results is in consonance with the findings of studies by Muui *et al.* (2013), Mucheru-Muna *et al.* (2007) and Tirol-Padre *et al.* (2007) who observed increased phosphorous contents in treatments amended with sole mineral fertilizers or fertilizers combined with manure. Cattle manure supplies macronutrients and micronutrients to the soil (Gemechu, 2020) and has been known to provide higher phosphorous levels to soil as compared to other organic inputs (Opala *et al.,* 2012).

5.2 Effects of *Zai* pit technology combined with selected ISFM amendment options on sorghum grain and stover yields

5.2.1 Effect on phenological parameters

Generally, less days to emergence were recorded in short rains seasons compared to long rains seasons. Similarly, days to 50% flowering and physiological maturity were equally less in the two short rain seasons compared to long rain seasons. Within seasons, days to emergence, 50% flowering and physiological maturity were generally less in treatments under *Zai* with organic amendments compared to similar treatments under conventional system.

The fewer days to emergence, 50% flowering and physiological maturity recorded in short rain seasons could be attributed to the sufficient amount of rainfall which was enough to meet the increased water requirements during the emergence and flowering stage compared to the long rain seasons where the rainfall received was minimal and thus soil moisture was not sufficient enough to ensure emergence and flowering occurred fewer days after sowing. In the long rain seasons, there were incidences of soil moisture stress as observed in the soil moisture content data. Sorghum crop water requirement increases from sowing to flowering and subsequently decreases during grain filling until the crop matures (Stichler & Fipps, 2003). Thus, higher amounts of rainfall received during the two short rains season (which corresponded to the time of flowering) contributed to higher yields observed in these seasons compared to the lower yields in the two long rain seasons.

In general, distribution of rainfall observed for the four study seasons denotes the continuing rainfall variability which strongly affects growth and development of sorghum and this contributed to the variability in the sorghum yield that were obtained from the four experimental seasons. These results correspond to the findings of Bosire and Karanja (2018) who observed fewer days to 50% flowering and physiological maturity in the short rain seasons with high amounts of rainfall compared to the other long rain seasons with little amount of rainfall. However, contradicting results were reported by Bosire and Karanja (2018) during the short rains season of 2014 (OND, 2014), where they attributed more days to 50% flowering in this season to the excess rainfall received during the month of November which led to water logging; hence removal of oxygen on which roots of sorghum could depend on for respiration.

Differences in number of days to emergence, 50% flowering and physiological maturity between treatments in each season was also observed. Fewer days to these phenological occurrences were recorded in treatments with organic amendments either solely or in combination with half rate mineral fertilizer in both *Zai* and conventional systems. This could be attricuted to the availability organic nutrients for uptake by the crops which boosted faster germination and flowering. This is in agreement with findings from previous studies (Gungula *et al.,* 2003; Bosire and Karanja, 2018). Similarly, Pannacci and Bartolini (2018) and Uchinio *et al.* (2013) observed that the application of N amendments increased the rate of plant development and shortened the time to flowering by 6 days relative to the unfertilized treatments.

The difference between treatments as a result of nutrient amendment was not significant and this agrees with the results of Moi (2021) where no significant difference was observed in days to 50% flowering at different levels of N applications. On the other hand, the observed phenological parameters took fewer days to be achieved in treatments under *Zai* system compared to conventional system. This could be as a result of the availability of sufficient moisture in the root zone for uptake by plants since the *Zai* design captures and stores water for longer periods thereby delaying the occurrences of soil moisture stress in the root zone.

5.2.2 Effect on sorghum grain and stover yields

Generally, the two short rains seasons (SR2018 and SR2019) recorded higher grain and stover yields as compared to the two long rains seasons (LR2019 and LR2020). This could be as a result of the high rainfall amounts (442.71 mm and 938.1 mm for SR2018 and SR2019 respectively) recorded in the short rains seasons (Figure 4.1) which were higher than those recorded in the long rain seasons (166.3 mm and 228 mm for LR2019 and

LR2020 respectively). The amount of rainfall received during the planting season appeared to have an effect on yield. The number of rainy days were also more during these two short seasons (Table 4.1) with more rainy days occurring during the first 62 days after planting (critical growth and developmental stages).

According to Hansen (2004), agricultural activities in eastern Kenya depends on the OND (October, November, December) short rainfall seasons which is more predictable and reliable. Thus, better annual yields are received during the OND seasons in most agriculture-depended households (Barron *et al.,* 2003; Amissah-Arthur *et al.,* 2002). The lower yields recorded during the LR2019 and the LR2020 seasons were as a result of the lower unreliable rainfall amounts, fewer number of rainy days and poor distribution during the season (McCarl *et al.,* 2008). These two seasons experienced long intra-seasonal dry spells (73 and 69 days for LR2019 and LR2020, respectively) which resulted to soil moisture stress, hence the low recorded yields. Intra-seasonal dry spells are a characteristic feature of semi-arid areas in East Africa (Barron *et al.,* 2003) and South Africa (Usman & Reason, 2004). The occurrence of these dry spells has had major detrimental effects on crop yields. In their study, McCarl *et al.* (2008) and Craufurd and Peacock (1993) found out that sorghum grain yields were reduced by 87% as a result of water stress which occurred during critical crop developmental stages such as flowering and stem swelling. According to Bewket (2009) and Mulat *et al.* (2004), the amount and temporal distribution of rainfall is generally the major determinant of inter seasonal fluctuations observed in crop production levels.

Zai pit is a form of ancient dryland farming technique which involves the utilization of basins or holes for agricultural activities so as to minimize the effects of droughts since they ensure soil maintenance, soil erosion control and water preservation (Danjuma & Mohammed, 2015; Sawadogo, 2011). In Kenya, *Zai* pits technology has been promoted as a water harvesting technique for maize production in eastern region (Recha *et al.,* 2014). The results of this study indicated that treatments under *Zai* pit technology with the selected soil nutrient amendment options had a significant ($p \leq 0.05$) positive interaction effect on sorghum grain and stover yields as compared to similar treatments under conventional system. Furthermore, higher yields were realized in *Zai* treatments containing either sole cattle manure or in combination with mineral fertilizer.

Despite the fertility inputs, the higher yields recorded under *Zai* treatments could be attributed to the potential of *Zai* pits in increasing the amount of water stored in the soil profile by trapping or holding rainwater where it falls (Mutunga, 2001), therefore delaying the onset and occurrence of severe water stress thus buffering the crop against damage caused by water deficits during dry periods (Nyamadzawo *et al.,* 2013). Besides enhancing water storage, *Zai* pits increases water retention and reduces run-off for plant uptake (Drechsel *et al.,* 1999) thereby, boosting crop yield. The results of this study correspond with other studies whose results indicated a positive effect of *Zai* pit utilization on crop yield. Fatondji *et al.* (2006) found out that the use of *Zai* pits in Burkina Faso led to increased harvests of pearl grain Millet. They attributed this increase to the use of *Zai* pits as well as the use of organic fertility inputs.

A study by Sawadogo (2011) reported increased yields variations from 300 to 400 kg ha^{-1} by the *Zai* system in degraded land. Sawadogo (2011) also reported substantial sorghum grain yield increases in farmer's fields from 319-642 kg ha^{-1} without *Zai* pit system to 975-1600 kg ha-1 with *Zai* pit system. The use of potential of *Zai* pit system in increasing crop yield has also been reported in Zambia (Thierfelder & Wall, 2009; Haggblade & Tembo, 2003), South Africa (Magombeyi & Taigbenu, 2008), Niger (Fatondji *et al.,* 2009), Ethiopia (Amede *et al.,* 2011) and in Zimbabwe (Gumbo *et al.,* 2012; Thierfelder & Wall, 2009). Besides its positive effect on soil moisture, *Zai* pits have a good potential to increase soil biological activities and to promote nutrient use and agronomic efficiency (Fatondji, 2002).

5.3 Effects of *Zai* pit technology combined with selected ISFM amendment options on soil aggregate stability and moisture content

5.3.1 Effects on aggregate stability

Soil aggregate stability, expressed as mean weight diameter (MWD), was significantly ($p \leq 0.01$) higher in all the *Zai* pit treatments in contrast to similar treatments in the conventional farming technique (Figure 4.4). Soils from *Zai* with integrated manure and chemical fertilizer recorded the greatest significant ($p \leq 0.01$) mean weight diameter of 2.06 mm, followed by *Zai* with sole manure (2.01 mm). In addition, under both systems, the treatments with organic amendments, whether solely or in combination with inorganic amendments, recorded higher mean weight diameter compared to those treatments without organic amendments (Figure 4.4). A higher mean weight diameter in treatments under *Zai* pit system imply very stable soils as compared to the low mean weight diameter values under conventional system.

High aggregation in *Zai* treatments is attributable to the minimal soil disruptions during the management and utilization of *Zai* pit system, thus macroaggregates are not broken down as is the case in conventional system where macroaggregates are broken down through ploughing (Ngetich *et al.*, 2014a; Twomlow *et al.*, 2008). Higher soil aggregation in *Zai* pit system could also be as a result of the high organic carbon contents in the low tillage systems (Bolo *et al.*, 2021; Ndung'u *et al.*, 2021). Mechanical breakdown of soil aggregates through cultivation is the reason behind the loss of soil organic carbon, and thus, *Zai* being a low-tillage system, there is minimal cultivation and reduced loss of soil organic carbon. Low or no cultivation farming technologies have been associated with high carbon levels (Al-Kaisi *et al.*, 2014).

Zai pits have the potential to store nutrients in place because to their design, minimizing losses through erosion and run-off. Previous research has found that the intensity of tillage activities has a significant impact on aggregate stability (Al-Kaisi *et al.*, 2014). Low-tillage systems have been found to have more stable soil aggregates than conventional farming methodologies (Caesar-TonThat *et al.*, 2011; Gathala *et al.*, 2011). Due to reduced soil disturbance, the *Zai* pit system is considered a low tillage technique in this study (Twomlow *et al.,* 2008). Previous researches have also reported higher aggregate stability under low or no tillage agricultural systems as compared to conventional systems characterized with high rate of soil disturbance through ploughing (Marumbi *et al.*, 2020; Bottinelli *et al.,* 2017; Khuzwayo, 2017; Caesar-TonThat *et al.*, 2011; Gathala *et al.*, 2011; Lal, 2008; Ngetich *et al.,* 2008).

Conventional cultivation has been shown to affect soil aggregation both directly and indirectly by disrupting macroaggregates and altering biological and chemical variables (Barto *et al.,* 2010). Lal (2008) also documented a decrease in aggregate stability in relation to conventional cultivation. Ngetich *et al.* (2008) and Ghuman and Sur (2001) found that the minimally tilled treatments recorded significantly high ($p \leq 0.05$) mean weight diameter of soil aggregates than the conventionally tilled treatments. As a result, when compared to low-tillage systems, conventional tillage causes less aggregation (Yalcin & Cakir, 2006). The low values of aggregate stability observed in treatments under conventional system could be associated to loss of soil organic carbon during tillage (Nyamangara *et al.,* 2014). Since minute adjustments in soil organic carbon can affect aggregate stability, the loss of organic matter associated with conventional tillage increases the vulnerability of soil aggregates to disruption (Nyamangara *et al.,* 2014; Nyamadzawo *et al.,* 2013; Verhulst *et al.,* 2010; Six *et al.,* 2000).

Additionally, highest mean weight diameter values in treatments under *Zai* pit technology were recorded under those treatments with manure amended soils, either solely or combined manure with chemical fertilizer. Despite the low aggregation recorded in treatments under conventional system, treatments amended with organic inputs recorded higher MWD compared to the control and those treatments amended solely with inorganic inputs under this system. The results also indicate higher soil organic carbon (SOC) in treatments with organic amendments under both systems (Table 4.6) at the end of LR2020 season. These findings may as a result of the binding properties of humic compounds and other by-products of microorganisms resulting from the organic amendments (Bolo *et al.,* 2021; Ndung'u *et al.,* 2021). Higher microbial biomass and, as a result, the generation of extracellular polysaccharides, which operate as a good binding agent of soil aggregates, could possibly have contributed to higher aggregate stability amongst organically amendment treatments. These findings corroborate with Huang *et al.* (2010), who observed increased aggregation under treatments amended with combined manure and mineral fertilizer. Organic matter has been found to be a major cementing agent for soil aggregation (Tisdall & Oades, 1982), hence the favorable impacts of organic input amendments on aggregation of soil particles in the current study, as indicated by Schjønning *et al.* (2002), can be attributed to increased aggregation linked with organic input (Yang *et al.*, 2017).

A substantial positive association exists between organic carbon and aggregate stability (Kushwaha *et al.,* 2001). Soil organic carbon enhances soil aggregation, whereas aggregates in return store soil organic carbon, decreasing its decomposition rate (He *et al.*, 2018). Soil aggregates lower the rate of soil organic carbon turnover by establishing a physical barrier between microorganisms and enzymes. on the other hand, soil organic carbon performs a significant role in stabilizing soil aggregates through enhancing microbial proliferation, which promotes the binding together of soil micro-aggregates together (Six *et al.*, 2000). According to Du *et al.* (2013), long-term fertilizers application, particularly organic fertilizers, increases aggregate stability on surface soil. They attributed the enhanced aggregate stability in organically treated soils to higher microbial biomass, whose by-products are suitable binding agent for soil aggregates.

The results of this study indicating higher mean weight diameter values recorded in treatments with organic inputs corroborate with the findings of previous studies where higher aggregate stability were reported in treatments with organic inputs (Bottinelli *et al.*, 2017; Du *et al.,* 2013; Ayuke *et al.,* 2011; Kushwaha *et al.*, 2001). A field experiment conducted by Wang *et al.* (2013) on China's Loess Plateau revealed improved aggregate stability in treatments treated with organic fertilizer while soils treated with no fertilizer exhibited reduced aggregation. The results of previous studies have also reported enhanced stability of soil aggregates in treatments with sustained incorporation of organic manures in various forms; composts, farmyard manure, crop residues, and straw returns, due to more accumulation of soil organic carbon and a constant supply of freshly broken-down carbon-containing materials (Ghosh *et al.,* 2018; He *et al.,* 2018; Benbi & Senapati, 2010; Chen *et al.,* 2010; Sodhi *et al.,* 2009; Singh *et al.,* 2007). Thus, the findings of the present-day study indicate that the interaction between *Zai* pit system and organic soil amendments significantly promotes soil aggregation thus resulting to more stable soil aggregates and the associated increase in soil organic matter contents.

5.3.2 Effects on soil moisture content

In all the four study seasons, across different days within each season, higher soil moisture contents expressed as volumetric water content values were recorded in treatments under *Zai* pit system as compared to their conventional counterparts (Figures 4.5, 4.6, 4.7 and 4.8). The observed higher volumetric water content values in treatments with *Zai* pit could be attributed to the water harvesting characteristic of *Zai* pit technology. The structure of the pits allows for more water to be captured in the pit thus enhancing moisture availability for infiltration and uptake by plants (Kimaru-Muchai *et al.,* 2021). The observed tendency can also be attributable to the function of *Zai* pits as basins, which trap infiltrating water, thus, limiting percolation and preserving water within the 0-30 cm soil depth. Moisture trapped in the *Zai* pits helps to delay the onset and incidence of moisture stress, thus protecting the crop from the effects of water shortages during periods of dry-spells (Nyamadzawo *et al.,* 2013).

Previous studies have reported higher soil moisture content in *Zai* pit treatments as compared to conventional systems (Zelelew *et al.,* 2018; Nyamadzawo *et al.,* 2013; Reij *et al.,* 2009; Mutunga, 2001). *Zai* pits favors infiltration of moisture into the soil compared to conventional system (Fatondji *et al.,* 2006). Findings by Vohland and Barry (2009) reported improved soil water storage in *Zai* treatments compared to conventional treatments. *Zai* pits have been proven to be capable of gathering up to 25% of run-off from 5 times their area (Malesu *et al.,* 2006). By capturing or storing precipitation water, *Zai* pits enhance the quantity of water retained in the soil layers (Mutunga, 2001). In addition to enhancing the water levels retained in the soil profile, *Zai* pits promote water penetration and reduce run-off, thereby making soil moisture available for plant uptake in the occurrence of dry periods (Drechsel *et al.,* 1999).

The volumetric water content values were generally highest in treatments with absolute manure input and those with combinations of manure and mineral fertilizers under both *Zai* and conventional systems (Figure 4.5, 4.6, 4.7 and 4.8). Higher volumetric water content in treatments amended with organic inputs could be linked to the improved soil particle aggregation in manure amended soils that might have improved water retention in the soil. Addition of manure into the soil also decreased evaporation rate of soil moisture from the soil by improving the soil's water retention capacity, thus the observed high volumetric water content values in manure-amended treatments. From the results of this study, organic amendments improved moisture retention to the lower layers in the soil profile. Manure application reduces compatibility and enhances moisture retention in semi-arid soils (Blanco-Canqui *et al.,* 2009). The findings of this study are in agreement with the observations of other previous studies where application of organic inputs led to enhanced soil moisture (Oduor *et al.,* 2021; Kaluli *et al.,* 2012; Shaheen *et al.,* 2010; Blanco-Canqui *et al.,* 2009; Overstreet & DeJong-Huges, 2009). The low volumetric water content values observed under convention treatments could be as a result of low water storage capacity (due to lack of depressional pits) and high evaporation (due to exposed ground).

5.4 Effects of *Zai* pit technology combined with selected ISFM amendment options on total soil organic carbon and its selected labile organic fractions

5.4.1 Total organic carbon (TOC)

Generally, under both systems, higher total organic carbon contents were recorded in treatments with organic inputs either solely or in combination with mineral fertilizer (Table 4.12). Higher total organic concentrations in manure amended soils could be attributed to a higher proportion of recalcitrant organic compounds in manure. The use of farmyard manure can result in an increase in lignin and lignin-like compounds, which are important components of the soil's resistant carbon pool (Lima *et al.,* 2009). Manure directly increases carbon inputs into the soil and also influences crop residues, which potentially sequestrates agricultural soil organic carbon and nutrient release. Manure inputs also improves crop production resulting in increased total carbon inputs from rhizodeposition and root biomass (Lin *et al.,* 2009). The observed significant high values in treatments under *Zai* system as compared to those under conventional system could be attributed to the low-tillage nature of *Zai* pit. Thus, there is reduced exposure to erosion and soil aggregation shields the carbon containing compounds from rapid breakdown by decomposers as it is the case in conventional plots.

Higher amounts of total organic carbon observed in treatments with organic amendment have also been reported in previous studies (Ndung'u *et al.,* 2021; Xin *et al.,* 2016; Zhou *et al.,* 2016; Kuzyakov & Blagodatskaya, 2015; Liu *et al.,* 2014; Liu *et al.,* 2013; Mucheru-Muna *et al.,* 2007). Regular additions of residues, compost, or manure can raise total soil organic carbon to a greater level (Li *et al.,* 2020). Lin *et al.* (2009) reported that substituting 100% or 50% of mineral fertilizers with organic manure over 15 years could increase total organic carbon compared to equivalent mineral fertilizer treatments in a trial in the North China Plain region.

Results of a study by Li *et al.* (2018b) revealed that treatments which received organic manure had significantly higher total organic carbon concentrations and stocks compared to the those with mineral fertilizer and control treatments, storing up to 35.39 mg.ha^{-1} more carbon in the top 20 cm soil layer. Numerous studies have reported that changes in soil organic carbon were induced by fertilization practices (Yang *et al.,* 2018, 2012; Wang *et al.,* 2015; Xu *et al.,* 2011; Yan *et al.,* 2007) and conservation tillage (Liu *et al.,* 2014; Wang *et al.,* 2014). A study by Li *et al.* (2018c) revealed that after nine years, application of organic fertilizers substantially increased soil organic content while application of chemical fertilizers alone did not affect soil organic levels compared with that of control.

Mineral fertilized treatments in both systems recorded the lowest total organic carbon levels relative to all the other treatments. This finding agrees with the results of other previous studies (Mucheru-Muna *et al.,* 2014, 2007; Yan *et al.,* 2007).

The impact of mineral fertilization on total organic carbon concentrations has been a subject of conflict in many reports (Reid, 2008; Khan *et al.,* 2007); some reports indicated that long-term use of mineral fertilizer could increase total organic carbon stocks in the topsoil layer (Fan *et al.,* 2014; Gong *et al.,* 2012; Johnston *et al.,* 2009) while other reports demonstrated that the use of mineral fertilization resulted to a decrease in total organic carbon concentrations in soil (Lou *et al.,* 2011; Mulvaney *et al.,* 2009; Khan *et al.,* 2007). Such differences seem to depend on the initial soil carbon status, the ecosystem under study and the nature, quantity and duration of fertilizer application (Hamer *et al.,* 2009; Reid, 2008). The total organic carbon concentrations in manure-amended soils suggest that manure addition may be a long-term strategy for improving soil organic carbon stabilization (Ding *et al.,* 2012).

In a long-term field experiment with a double rice cropping system carried out in Andhra Pradesh, India, Anantha *et al.* (2020) reported higher total organic carbon contents with joint application of combined mineral fertilizer and organics. The study reported little change in total organic carbon with 100% mineral fertilizer application compared with the control. Total organic carbon levels in soils reflect the long-term balance between additions and losses of organic carbon. Various studies have shown that increases in total organic carbon levels are directly related to the amounts of organic residues added to soils, in fertilizer and manure application (Lemke *et al.,* 2010; Hati *et al.,* 2007; Cai & Qin, 2006).

Total organic carbon is made up of two major pools: a labile fraction and a stable fraction (Ding *et al.,* 2012). The stable fraction makes up the majority of the total organic carbon and has turnover rates of thousands of years. As a result, soil management measures have little impact on its content (Xu *et al.,* 2011). Because the labile percentage has a substantially shorter turnover time, usually less than 10 years (Janzen *et al.,* 1992), it is changed much more quickly by changes in organic matter inputs or losses caused by management. It has therefore been suggested as an early indicator of the effects of soil management and cropping systems on total organic carbon quality and quantities (Ding *et al.,* 2012).

5.4.2 Particulate organic carbon (POC)

Particulate organic carbon is considered to include decomposing plant and animal residues that have rapid turnover rates, consistent with the theoretical characteristics of total organic carbon pools of intermediate lability (Tong *et al.,* 2014). Generally, significantly ($p \leq 0.05$) higher particulate organic carbon concentration was recorded in treatments under *Zai* pit system as compared to those under conventional system. Additionally, the treatments with organic amendments either solely or in combination with mineral fertilizer recorded significantly ($p \leq 0.05$) higher particulate organic carbon content as compared to the treatments without organic inputs (Figure 4.9).

The higher particulate organic carbon contents recorded in treatments under *Zai* system could be attributed to the exclusion of excessive soil mixing which always occurs in the case of conventional tillage. Therefore, particulate organic carbon, as all other soil labile organic fractions, is preserved through soil aggregation which limits their accessibility to the decomposer community. Systems characterized by minimum or no-tillage, according to Chen *et al.* (2009), not only limits intimate interactions between crop residues and mineral particles, but also protects labile carbon components from breakdown through soil agglomeration, inhibiting their availability to the decomposer population.

The high particulate organic carbon contents in organically amended treatments, either solely or in combinations with mineral fertilizer could be attributed to the direct addition of carbon into the soil labile organic pool. Also, as suggested by Zhu *et al.* (2015), the observed trend could be as a result of increased microbial activity in organically modified soils resulting to breakdown of plant residue and conversion of plant residue-carbon into labile forms of organic carbon. The lower levels of particulate organic carbon recorded in conventional plots could be attributed to tillage practices, which enhances particulate organic carbon decomposition by disturbing soil aggregates (Smith *et al.*, 2012).

Particulate organic carbon levels in soil have been used to identify the effects of fertilization on soil organic matter in many studies (Wander, 2004). Particulate organic carbon concentrations have been found to be elevated in farming systems relying on organic fertility compared with those using synthetic fertilizers (Fortuna *et al.*, 2003; Nissen & Wander, 2003; Wander *et al.*, 1994). The results of this study corroborate with the findings of Yang *et al.* (2012) who reported highest level of particulate organic carbon in treatments with two levels of manure application (13.7 t ha^{-1} and 20.6 t ha^{-1}) plus mineral fertilizer followed by treatments with sole mineral fertilizer, while the control yielded the lowest levels. They also reported no significant differences between the control and chemical fertilizer treatments.

Pure organic manure treatments showed significantly higher concentrations of particulate organic carbon as compared to integrated treatments and sole mineral-fertilized plots in a study carried out in China by Li *et al.* (2018b). Highest proportion of particulate organic carbon was observed under treatments amended with 60 kg N ha^{-1} organic manure, which was not significantly different from integrated 30 kg N ha^{-1} organic manure and 30 kg N ha^{-1} mineral fertilizer. In their study, treatments with standard rate of mineral fertilizer had a lower proportion of particulate organic carbon and the lowest proportion was found in the control treatment.

Similarly, Tong *et al.* (2014) reported highest particulate organic carbon fractions in the soils under the treatments with manure either solely or in combination with mineral fertilizer at different manure rates (sole manure, 1:1 and 1.5:1 ratio manure to mineral fertilizer). The results revealed that the three manure application levels were averagely 3.9, 3.8 and 3.3 times higher, respectively, than sole mineral fertilizer-treated soils, and 4.9, 5.6, and 10.2 times higher, respectively, than the control.

Comparably, the findings of long-term field experiment carried out in the Institute of Red Soil, Jiangxi Province, China, to examine the responses of crop yields, total soil organic carbon and its labile fractions to the effects of long-term fertilization, reported highest carbon concentration of the particulate organic carbon fraction, which was 2.8 and 3.1 times greater, in the sole manure and manure combined with mineral fertilizer than in the control, respectively (Huang *et al.*, 2010).

The significantly lower particulate organic carbon concentrations observed in chemical fertilized-treatments could be as a result of accelerated decomposition as caused by the addition of nitrogen in the chemical fertilizer. Li *et al.* (2018a) and Kirkby *et al.* (2014) explained that the availability of nitrogen from addition of chemical fertilizers may also promote the decomposition of soil organic carbon and its labile organic fractions.

5.4.3 Permanganate oxidizable carbon ($KMnO_4$-C)

Zai with manure and mineral fertilizer had the highest (4.69 g.kg^{-1}) significant ($p \leq 0.05$) influence on $KMnO_4$-C which was 5% higher than the amount recorded under conventional with manure and mineral fertilizer (4.46 g.kg^{-1}). Generally, all treatments under *Zai* system recorded significantly ($p \leq 0.05$) higher $KMnO_4$-C amounts compared to similar treatments under conventional treatments. The trend was similar to that observed in particulate organic matter with significantly higher $KMnO_4$-C values being recorded under treatments with manure amendments either solely or in combination with mineral fertilizer (Table 4.13).

All the treatments recorded higher $KMnO_4$-C values than the control. The higher $KMnO_4$-C rates recorded in treatments under *Zai* system could be attributed to low tillage, a characteristic of *Zai* technology. With minimal disturbance of soil particles, $KMnO_4$-C is held up within the soil aggregates and not exposed to loss through erosion. Minimal soil aggregate disturbance due to low tillage also translates to low rates of breakdown of this carbon fraction through microbial activities, thus, the high amounts of $KMnO_4$-C in *Zai* pits. The high $KMnO_4$-C contents in organically-amended soil is still attributable to direct addition of labile organic carbon from the manure and mineral fertilizer inputs.

$KMnO_4$-C, the fraction of labile carbon which is obtained from chemical oxidation methods using potassium permanganate (Blair *et al.,* 1995), has since been considered as an early sensitive index for the impacts of long-term applications of fertilizers or organic resources on the dynamics of the active total soil organic carbon fractions (Xu *et al.*, 2011; Mtambanengwe & Mapfumo, 2008). Since $KMnO_4$-C can respond rapidly to changes in carbon supply, it is considered an important indicator of soil quality (Xu *et al.*, 2011). The findings of this study are in agreement with the results of a study by Li *et al.* (2020) which revealed that plots receiving organic manure had significantly higher $KMnO_4$-C compared to mineral-fertilized plots and the control. $KMnO_4$-C concentrations were higher when double the rate of manure was used. The impacts of different fertilizer treatments on the proportion of $KMnO_4$-C were similar to that of particulate organic carbon, with highest proportions occurring in treatments with double the standard rate or organic manure and lowest concentrations occurring in the control.

Similarly, Bhardwaj *et al.* (2019) reported highest $KMnO_4$-C in farmyard manure treated soils as compared to sole mineral fertilizer-amended and the control treatments in the 0-15cm soil depth. Comparably, in a study by Zhang *et al.* (2020), compared with the control, $KMnO_4$-C was significantly greater ($P \leq 0.05$) by 39% and 61% under sole organic treatment and the combined organic and inorganic treatment, respectively. Moreover, the $KMnO_4$-C concentrations in plots under the combined organic and inorganic treatment was 16% higher than in plots under the sole inorganic amendments. This is similar to the results of the present study where higher $KMnO_4$-C concentrations was recorded in sole manure-amended treatments, followed by manure combined with mineral fertilizer treatments while the least being recorded under the control.

The findings of this study are also consistent with that of Yang *et al.* (2012) where plots receiving organic materials (single rate and double manure combined with mineral fertilizer) had substantially higher $KMnO_4$-C than those receiving chemical fertilizers and the control plot. In their study, no significant differences among the organic amendment treatments, nor among the chemical fertilization treatments was observed. Similarly, Yang *et al.* (2012) attributed the high $KMnO_4$-C in the organic material-amended soils than in the chemical fertilizer-treated soils to labile carbon inputs associated with the straw and manure. Blair *et al.* (2006) and Rudrappa *et al.* (2006) both made similar observations. Rudrappa *et al.* (2006) observed considerably greater $KMnO_4$-C concentrations in chemical fertilizer-treated soils than in controls, as well as significant variations amongst various treatments with amended with chemical fertilizer. This is consistent with this present study where all the chemical fertilizer-amended treatments recorded significantly higher $KMnO_4$-C contents than the control.

Verma *et al.* (2010) found higher concentrations of $KMnO_4$-C after manure amendments in wheat-maize and rice-wheat systems, which are likely related to the amounts of lignin supplied in the treatments amended with organics combined with inorganic inputs. Similarly, the present-day study indicated that $KMnO_4$-C was higher in manure-treated soils compared to mineral-fertilized soils and unfertilized soils, confirming that manure inputs drive changes in pools of labile carbon as seen in the other carbon fractions.

In contrast to the findings of this study and similar findings in other studies, Mtambanengwe and Mapfumo (2008) found no significant variations in the $KMnO_4$-C content of soil as a result of nutrient management strategies. Differences in characteristics such as soil type, cropping system, and climate in the analyzed systems could explain the disparities in results from diverse studies. These disparities also suggest that simply measuring the $KMnO_4$-C concentrations cannot be considered sufficient to distinguish between effects of different nutrient management inputs, at least in the experimental conditions of a study such as this.

5.4.4 Light Fraction Organic Carbon (LFOC)

The light fraction organic carbon content in the soil was also significantly affected by the soil management regimes. The trend in light fraction organic carbon values among treatments was generally similar to that observed in the other carbon fractions with higher values being recorded in treatments under *Zai* pit system and those with organic inputs either solely or in combination with inorganic inputs. The highest light fraction organic carbon value was recorded in *Zai* with sole manure (2.51 g.kg^{-1}) while the lowest were found in conventional with no input (1.47 g.kg^{-1}) (Figure 4.10). The observed trends could be attributed to low tillage activities characterized with *Zai* system and the direct addition of labile carbon to the soil though the addition of organic inputs. The high light fraction organic carbon observed in treatments with organic inputs could also be attributed to the increased microbial activity in organically-amended soils resulting to decomposition and conversion of plant residue-carbon into labile forms of organic carbon.

The results of this study corroborate with that of Yang *et al.* (2012) who observed that treatments with double standard rate of manure combined with mineral fertilizer resulted in the highest light fraction organic carbon content, and significantly higher contents of this carbon fraction than all the other treatments. These findings also agree with Yuan *et al.* (2021), who concluded that a high input of organic matter could increase soil light fraction organic carbon after observing high amounts of this carbon fraction in plots treated manure combined with mineral fertilizers.

Consistent with the findings of this study, incorporation of organics into the soil significantly increases the content of active soil carbon fractions such as the light fraction organic carbon (Mi *et al.,* 2019; Xu *et al.,* 2011). Similarly, the results of a study by Li *et al.* (2018c) indicated that straw or manure amendment directly contributed to higher light fraction organic carbon contents in treatments that had sole manure, manure with straw and manure combined with mineral fertilizer. This is likely due to the fact that organic inputs contain a lot of labile organic matter (Liu *et al.,* 2014; Six *et al.,* 2000) and are a source of carbon for microbial activity that transforms the carbon in them into labile organic carbon.

At various stages of decomposition, residues of plants, microorganisms and soil animals make up the majority of the light fraction organic carbon. This carbon fraction contains greater amounts of carbohydrate constituents, lignin derivatives and aliphatic compounds than does particulate organic carbon and is more closely related to plant residues (Yan *et* *al.*, 2007). The light fraction is a readily decomposable substrate for soil microbes as well as a short-term nutrient reserve for plants (Wu *et al.*, 2004). As a result, light fraction is more sensitive to recent plant residue and organic inputs than total organic matter in soils, and hence can provide a clearer indication of the effects of soil management and cropping regimes (Gregorich *et al.*, 1994; Janzen *et al.*, 1992).

In this study, the proportion of organic carbon was greater in particulate organic carbon than in light fraction organic carbon in all treatments under the two systems, as was reported in other studies (Yan *et al.*, 2007; Gregorich *et al.*, 2006). Significant quantities of carbon from organic inputs are likely retained in soil particulate fractions (Zhu *et al.*, 2015), thus the observed differences. The results of this study are supported by numerous reports (Yu *et al.*, 2020; Ibrahim *et al.*, 2015; Yang *et al.*, 2012) indicating that higher carbon input induced by fertility management practices resulted in significantly larger labile organic carbon pools such as the light fraction organic carbon. Gosling *et al.* (2013) confirmed that light fraction organic carbon contents were strongly influenced by factors related to the recent history of organic matter addition to the soil.

5.4.5 Dissolved organic carbon (DOC)

The trend in dissolved organic carbon contents among treatments was similar to that observed in the total organic carbon contents, with significantly ($p \leq 0.05$) high values being recorded under treatments with organic inputs either solely or in combination with mineral fertilizer. Additionally, significantly ($p \leq 0.05$) higher dissolved organic carbon was recorded in *Zai* pit system as compared to conventional system, indicating that the *Zai* pit system had a positive influence on the dissolved organic carbon (Table 4.14). The significantly high dissolved organic carbon contents observed in treatments under *Zai* can be attributed to the minimal tillage nature of the *Zai* pit system. As a result, dissolved organic carbon is not lost during destruction of soil aggregated and the associated increased respiration. Thus, in the *Zai* system, the dissolved organic carbon is held within the soil aggregates for a long time and their decomposition is much slower as compared to the conventional system.

Additionally, the significantly high dissolved organic carbon content recorded in treatments with organic amendments as compared to those without could be attributed to the direct addition of labile carbon into the soil through addition of organic inputs. Manure application directly contributes to the labile organic carbon pool and indirectly affects the conversion of plant residue-carbon into labile forms by enhancing microbial activity (Poirier *et al.*, 2013).

The current findings are consistent with previous research reporting higher levels of dissolved organic carbon under practices with minimum to zero tillage (Kumar *et al.*, 2018; Yang *et al.*, 2018; Lewis *et al.*, 2011; Chen *et al.*, 2009). According to Lewis *et al.* (2011), increased tillage intensity can lower dissolved organic carbon levels in soils by destroying soil macroaggregates and enhancing respiration activities. Due to increased soil disturbances, the aggregate-protected labile carbon fractions are subjected to rapid breakdown via oxidation, resulting in a lower amount of dissolved organic carbon under conventional system.

Dissolved organic carbon matter is an important labile fraction since it is the main energy source for soil microorganisms; a primary source of mineralizable nitrogen, phosphorous and sulphur, and it influences the availability of metal ions in soils by forming soluble complexes (Jinbo *et al.*, 2006). It is produced from decomposition of soil organic matter mainly driven by soil microbes (Zhu *et al.*, 2015). Dissolved organic carbon is a measure of carbon easily transportable within ecosystems (Neff & Asner, 2001). It plays a valuable role in nutrient turnover and the development of microbial populations.

The higher concentrations of dissolved organic carbon in organically amended treatments in this study is consistent with the results reported by (Li *et al.*, 2016; Zhu *et al.*, 2015). Li *et al.* (2018a) who found out that dissolved organic carbon content was highest in only manure-treated soils and lowest in soils treated with only mineral fertilizer or the control. Their study revealed that increasing manure input levels resulted in higher levels of dissolved organic carbon and that integrated treatment of manure combined with mineral fertilizer markedly increased dissolved organic carbon content compared to control.

Organic matter (organic manure or crop residues) additions to soil over time have been demonstrated to increase dissolved organic carbon contents (Liu *et al.,* 2017; Liu *et al.*, 2014; Liu *et al.*, 2014b, 2013; Xu *et al.*, 2011; Gong *et al.*, 2009). Several studies have reported significant increases in dissolved organic carbon with addition of manure (Li *et al.*, 2018b; Yang *et al.*, 2012). The studies have implied that sole manure application or in combination with mineral fertilizer provides a readily available source of carbon (Lou *et al.*, 2011).

The significantly lower dissolved organic carbon concentrations recorded in sole chemical fertilizer-amended treatments in both systems could be due to increased carbon consumption by soil microbes as a result of accelerated decomposition of both crop residues-carbon and the native total soil organic carbon. This is in agreement with the findings reported in previous investigations where the use of synthetic fertilizer (Nitrogen) induced a net loss of total soil organic carbon and its labile organic fractions due to accelerated residue breakdown by microbes and initial total soil organic carbon decomposition (Khan *et al.*, 2007; Yan *et al.*, 2007). The inability of total soil organic carbon and its labile organic fractions to respond to chemical fertilizer application rates can be attributed to two factors: 1) the amount of carbon input as crop residues can be used for microbial processes (Brown *et al.*, 2014) and 2) high nutrient concentrations (especially nitrogen) in the mineral fertilizer accelerate the decomposition of both litter and total soil organic carbon (Kirkby *et al.*, 2014).

5.5 Effects of *Zai* pit technology combined with selected ISFM amendment options on soil microbial biomass (C&N)

5.5.1 Soil microbial biomass carbon (SMBC)

Soil microbial biomass carbon was significantly affected by the planting system and amendments application. The results indicate that *Zai* pit system significantly ($p \leq 0.05$)

increased microbial biomass carbon compared to the conventional system. It is also evident from the results that, organic amendments had a significant influence on microbial biomass carbon whether applied solely or in combination with inorganics (Figure 4.11).

The high microbial biomass carbon concentrations recorded in the treatments under *Zai* system than those under conventional system implies *Zai* technology had a significant positive impact on microbial activity. This could be attributed to the accumulation of organic carbon fractions in soil due to the low-tillage nature of the *Zai* technology. The accumulated labile carbon fractions offer sufficient food for microorganisms and thus, maintains a higher microbial biomass carbon concentration. In contrast to conventional system, where a sudden flush of microbial activity with tillage events results in considerable losses of carbon as carbon dioxide, the lack of soil disturbance under *Zai* system offers a consistent source of organic carbon substrates for soil microorganisms, which boosts their activity and contributes to increased soil microbial biomass carbon. Also, the minimum-tillage characteristic of *Zai* system guards the soil aggregates by holding fungal networks built from carbon in place. Soil aggregates are an important habitat for the soil microbial biomass, hence high soil microbial populations resulting to high microbial activities, thus the observed significantly high microbial biomass carbon in treatments under the *Zai* system.

Another possible reason for the high microbial biomass carbon concentrations recorded in treatments under *Zai* system could be due to availability of sufficient moisture for microbial activities in the soil. Unlike the conventional system, *Zai* pits are designed mainly for soil moisture retention. There are greater soil moisture losses through evaporation in the conventional system as a result of the soil disturbance through tillage. The high microbial biomass carbon accumulation in treatments amended with organic inputs (manure) in both systems could be as a result of the increased availability of organic carbon substrates for microbial activities. Manure application can directly contribute to the labile organic carbon pool and indirectly affect the conversion of plant residue-carbon into labile forms by enhancing microbial activity (Li *et al.,* 2018b).

The results of the current study are in tandem with the findings of a field experiment conducted by Li *et al.* (2020) to investigate the effects of manure and inorganic fertilizer on total soil organic carbon and its labile organic fractions in a wheat-maize rotation on the North China Plain. Their study reported increased microbial biomass carbon in manure amended-treatments as compared to the treatments with chemical fertilizer amendments and the control. In China, Li *et al.* (2018b) reported a significant increase in microbial biomass carbon concentration with increasing rate of organic manure application in long-term fertilization experiment. The results of that experiment demonstrated that long-term application of organic manure alone resulted in a significant increase in microbial biomass carbon compared to mineral-fertilized plots and the control.

Similar to the results of this study, significant increases in microbial biomass carbon with addition of manure have been reported by other previous studies, implying that organic manure, alone or in combination with mineral fertilizers, has favorable impacts on microbial activity, most likely by providing a readily accessible pool of carbon substrate (Li *et al.,* 2020; Kumar *et al.,* 2018; Li, *et al.,* 2018c; Yang *et al.,* 2018, 2012; Naresh *et al.,* 2017; Lou *et al.,* 2011). In China, the results of a field experiment with winter wheat and summer maize conducted by Li, *et al.* (2018a) indicated microbial biomass carbon concentrations in treatments with combined manure and mineral fertilizer was 102% higher than that recorded in the control.

Mineral fertilizer effects on microbial biomass carbon have been documented in a variety of ways, including positive, negative, and no effects (Lou *et al.*, 2011; Gong *et al.*, 2009; Xue *et al.,* 2006). The significantly ($p \leq 0.05$) lower microbial biomass carbon concentration in treatments with mineral fertilizer amendments has also been documented in previous similar studies (Li *et al.,* 2020; Kumar *et al.,* 2018; Gong *et al.,* 2012). The significantly higher ($p \leq 0.05$), compared to the control, microbial biomass carbon concentrations recorded in treatments with mineral fertilizer amendments in this study are in line with the findings of Li *et al.* (2018c) where the microbial biomass carbon concentrations recorded in treatments with sole mineral fertilizer were 38% higher than the control. Soil microbial biomass carbon, which serves as a sink for labile nutrients or a source of nutrients for biota, has been extensively used to assess soil fertility under long-term fertilization regimes (Li *et al.,* 2015). Microbial biomass carbon is indicative of the size of the microbial biomass that does the decomposing (Powlson *et al.*, 2012).

5.5.2 Soil microbial biomass nitrogen (SMBN)

A significant ($p \leq 0.05$) difference in treatment effect was observed among treatments under the two systems with regards to their effect on microbial biomass nitrogen, with treatments under *Zai* pit system recording significantly ($p \leq 0.05$) higher microbial biomass nitrogen values as compared to their counterpart treatments under conventional system. *Zai* with sole manure recorded the highest microbial biomass nitrogen value while the lowest value was recorded under conventional with sole mineral fertilizer (Figure 4.12). Generally, the trend among treatments under the two systems was similar to that observed under microbial biomass carbon, with high values being recorded in treatments with organic amendments either solely or in combination with mineral fertilizer implying a positive effect of organic inputs on microbial biomass nitrogen.

Observed significantly high soil microbial biomass nitrogen concentrations in treatments under *Zai* system and those with organic amendments either solely or in combination with mineral fertilizer could be attributed to the same factors as those indicated in soil microbial biomass nitrogen. First, *Zai* is a minimum-tillage system and so losses through gaseous emissions is on the minimal, unlike in conventional system where the continuous soil disturbance through tillage activities enhances soil microbial biomass nitrogen losses through gaseous emissions. The minimum-tillage characteristic of *Zai* system also protects soil aggregates and do not break fungal networks, which are an important habitat for the microbial biomass in soil, hence high soil microbe populations resulting to high microbial activities. Secondly, the high moisture retention associated with the *Zai* pit system enhances microbial activities, thus the observed significantly high soil microbial biomass nitrogen concentrations in treatments under *Zai* system as compared to those under conventional systems.

On the other hand, the significantly high soil microbial biomass nitrogen values recorded in treatments with organic amendments either solely or in combination with inorganics, under both systems, could be as a result of the direct addition of organic carbon substrates that provides sufficient food for the soil microbes thus enhancing microbial activities. Also, organic inputs improve soil water retention which provide favorable conditions for increased microbial activities. Similar observations were documented by Kumar *et al.* (2018) where significant increase in soil microbial biomass nitrogen in surface soil (0–15 cm) was maintained in plots receiving fertilizer over unfertilized control plots.

Findings of this study are consistent with previous research where significantly higher soil microbial biomass nitrogen were recorded under systems characterized by reduced or zero tillage activities than the control (Naresh *et al.,* 2017; Dou *et al.,* 2016; Wang *et al.,* 2015; Wang *et al.,* 2014; Chen *et al.,* 2009; Carpenter-Boggs *et al.,* 2003). By enhancing soil aggregation and minimizing oxidation, zero/reduced tillage methods, such as *Zai* pits, allow carbon to build up in the plow layer, thus increased microbial activities (Carpenter-Boggs *et al.,* 2003).

Similar findings were documented by Xu *et al.* (2018) in an experiment to assess the effects of fertilization management practices on soil microbial biomass in Paddy Soil. The results of their study revealed soil microbial biomass nitrogen contents in treatments with combined organics and inorganics inputs were significantly higher ($p \leq 0.05$) than under the values recorded under treatments with sole mineral fertilizers and the untreated controls. Liu *et al.* (2017) also reported that combined application of chemical fertilizer and organic matter is the best way to increase soil microbial biomass and the resultant nitrogen contents in soil. Comparable studies corroborating our findings reported significantly high soil microbial biomass nitrogen contents in long-term experiments under combinations of organic and inorganic soil amendment (Oladele *et al.,* 2019; Li *et al.,* 2016). Contradicting findings were documented by Kallenbach and Grandy (2011) who reported no effect on soil microbial biomass nitrogen after application of organic amendment, suggesting that changes in microbial biomass (both carbon and nitrogen) cannot be attributed to amendment of soils with organic inputs only. In other similar studies, mineral fertilizer administration resulted in a 12%–48% drop in soil microbial biomass nitrogen when compared to no fertilizer or the initial values of the studies (Qiu *et al.,* 2016). Several studies have found that manure application, either solely or integrated with mineral fertilizer, increased soil microbial biomass (both carbon and nitrogen) in agricultural systems (Ren *et al.,* 2019). However, despite this, some researchers have suggested that the response of microbial biomass can be highly variable depending on soil types, management practices, and climate conditions (Lentendu *et al.*, 2014; Esperschütz *et al.,* 2007).

Manure, whether used solely or integrated with inorganic inputs, in contrast to typical sole mineral fertilizer, can boost carbon availability for soil microbes by delivering a high rate of exogenous carbon into soil, which can be helpful for increasing microbial biomass when compared to mineral fertilizer application alone (Neufeld *et al.,* 2017).When comparing manure application to solitary mineral fertilizer application, Pan *et al.* (2009) found that manure application improved soil microbial biomass nitrogen by 49%. As a result, manure amendment could be a viable alternative to mineral fertilizer application because it can boost soil bio-fertility (Li *et al.,* 2015; Pan *et al.,* 2009).

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

- Application of sole manure or combined with mineral fertilizer significantly increased soil pH, electrical conductivity, soil organic carbon and extractable phosphorous as compared to treatments with sole mineral fertilizer.
- Significantly higher yields were obtained from the *Zai* pit treatments with manure amendment either solely or in combination with mineral fertilizer.
- Soil aggregate stability was significantly higher in treatments under *Zai* technology with organic amendment compared to similar treatments under conventional system, across the four study seasons.
- Additionally, significantly high soil moisture contents values, expressed as volumetric water content, were recorded in treatments under *Zai* pit technology with organic amendments as opposed to comparable treatments under conventional system.
- Higher concentrations of total organic carbon (TOC), particulate organic carbon (POC), permanganate oxidizable carbon ($KMnO_4$-C), light fraction organic carbon (LFOC) and dissolved organic carbon (DOC) were recorded in treatments under *Zai* pit technology with organic amendments either solely or combined with inorganic fertilizer compared to the conventional system.
- Higher concentrations of soil microbial biomass (carbon and nitrogen) were recorded in treatments under *Zai* pit technology as compared to the conventional system.
- Application of organic manure, either solely or combined with mineral fertilizer significantly increased the concentrations of both microbial biomass carbon and nitrogen, compared to mineral fertilizers.

6.2 Recommendations

1. Farmers in drier regions characterized by low erratic rains and low soil moisture incidences should be encouraged to adopt and utilize *Zai* pit system as a farming

strategy for improved soil fertility and increased crop yield, as has been demonstrated in this study.

2. Sole organic and integrated organic and inorganic soil input amendments are paramount in enhancing soil fertility and intensifying crop yields in both *Zai* pit and conventional practices as has been demonstrated by this study.
3. In drier areas characterized by low soil moisture, *Zai* pit adoption and utilization is highly recommended for agricultural activities due to its added advantage in enhancing moisture availability in the rootzone for longer periods.
4. Agricultural policies, programs and projects by the County Government of Kitui and other stakeholders aimed improving food security at household level should be informed by well documented research findings, such as this, to avoid the usual failure of funded agricultural projects due to lack on proven experimental trials to guide the operations.
5. Based on the findings, agricultural policymakers should establish and implement adequate agricultural guidelines for extension service providers and smallholder farmers on the efficiency and effectiveness of the *Zai* pits.

6.3 Suggestions for further studies

1. Further on-farm research is needed to assess the economics of the *Zai* pits in combination with selected integrated soil fertility management options.
2. Research should be conducted with different sized *Zai* pits to establish their impacts on soil nutrient, soil moisture content and crop yield differently, in order to promote informed decisions on the adoption and utilization of *Zai* pit technology based on size.
3. Research aimed at assessing the influence of *Zai* pit technology on the productivity of different crops in different regions is also suggested.
4. Long term utilization of *Zai* pit technology on large scale production of commercial crops should be conducted to ascertain the economic benefits of *Zai* utilization for commercial projects.

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APPENDICES

Appendix 1: *Zai* pit establishment in the study site

Appendix 2: Preparation of conventional plots

Appendix 3: Gadam sorghum variety, experimental test crop for the study

Appendix 4: Dry sorghum head ready for harvest

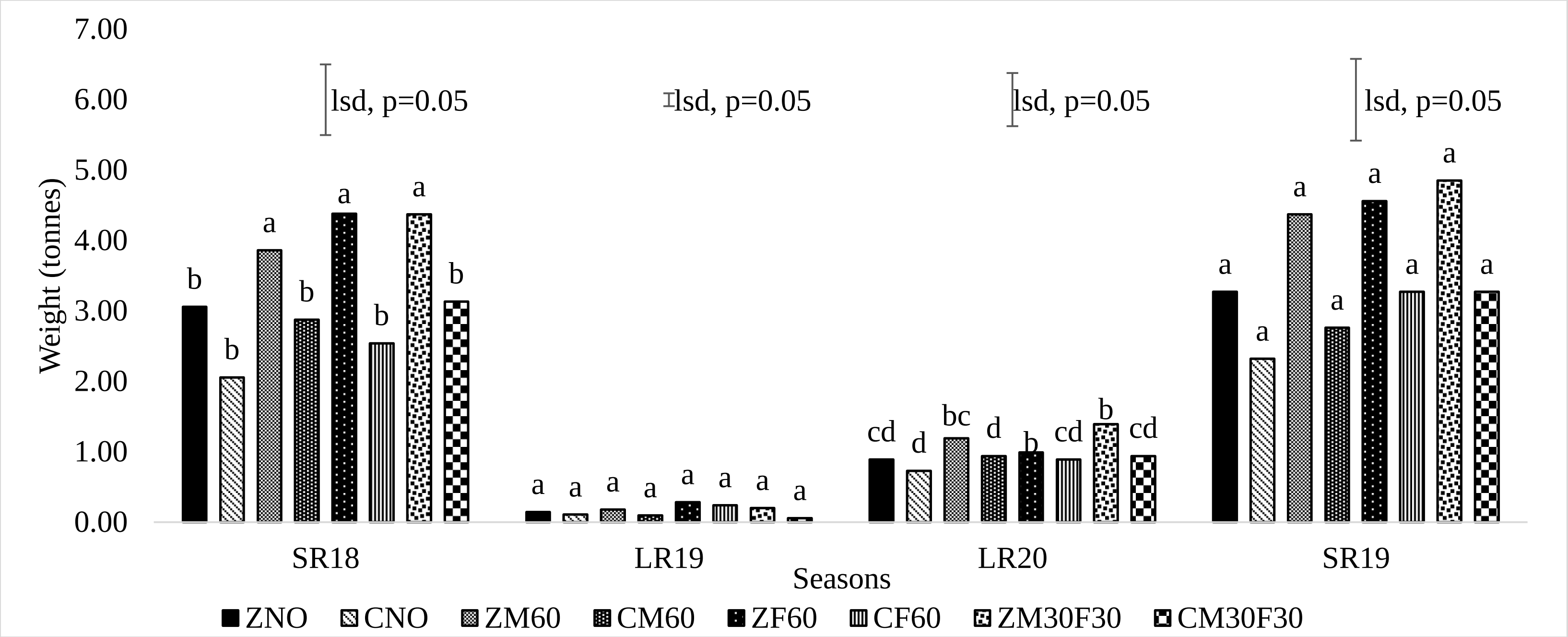
Appendix 5: Gadam sorghum grain after threshing

Appendix 6: Soil pH, Electrical conductivity (mS/m), Total nitrogen (%), Total organic carbon (%) and Extractable phosphorous (ppm) (0-15 cm) at the start of 2018 short rains and end of 2020 long rain seasons at Kabati, Kitui County

Soil Parameter	**Soil pH**			**Electrical Conductivity (mS/m)**			**Total Nitrogen (%)**			**Total Organic Carbon (%)**			**Extractable Phosphorus (ppm)**		
Treatments	**Beg**	**End**	**t-test**	**Beg**	**End**	**t-test**	**Beg**	**End**	**t-test**	**Beg**	**End**	**t-test**	**Beg**	**End**	**t-test**
ZNO	5.40^{a}	5.45^{bc}	2.76	249.8^{a}	394.7^{a}	5.38*	0.33^{a}	0.19^{b}	14.13*	1.33^{a}	1.57^{a}	-1.03	12.8^{a}	20.4^{c}	-2.05
CNO	5.44^{a}	5.55^{b}	1.35	183.8^{a}	298.4^{d}	10.76*	0.31^{a}	0.16^{c}	3.44	1.07^{a}	1.65^{a}	-3.07*	8.84^{a}	19.78^{c}	-2.27
ZM60	5.59^{a}	5.89^{a}	4.71*	209.9^{a}	383.4^{ab}	4.45*	0.38^{a}	0.18^{bc}	6.27*	1.12^{a}	1.91^{a}	-4.49*	11.02^{a}	27.7^{bc}	-3.69*
CM60	5.58^{a}	5.88^{a}	3.46*	194.1^{a}	360.1^{bc}	8.84*	0.31^{a}	0.19^{b}	4.99*	1.35^{a}	1.69^{a}	-3.16*	7.10^{a}	25.59^{bc}	-2.49
ZF60	5.49^{a}	5.25^{c}	4.1	210.7^{a}	366.8^{bc}	6.23*	0.46^{a}	0.16^{c}	2.74	1.37^{a}	1.51^{a}	-0.56	10.2^{a}	66.97^{a}	-6.97*
CF60	5.43^{a}	5.32^{c}	3.96	192.3^{a}	343.8^{c}	9.60*	0.39^{a}	0.15^{cd}	10.78*	1.28^{a}	1.55^{a}	-1.06	6.37^{a}	16.01^{c}	-4.35
ZM30F30	5.59^{a}	5.82^{a}	5.42*	200.2^{a}	360.5^{c}	8.59*	0.38^{a}	0.17^{bc}	4.13*	1.36^{a}	1.60^{a}	-1.32	8.74^{a}	53.31^{ab}	-1.86*
CM30F30	5.53^{a}	5.78^{ab}	4.04*	234.8^{a}	388.0^{a}	9.15*	0.38^{a}	0.21^{a}	5.31*	1.44^{a}	2.22^{b}	-1.52	15.3^{a}	27.7^{bc}	-4.32*
LSD	0.33	0.42		62.28	30.91		0.16	0.03528					31.95	31.95	
P-value	0.74	0.0128*		0.28	0.02127*		0.47	0.01423 *		0.59	0.24		0.1047	0.0179*	

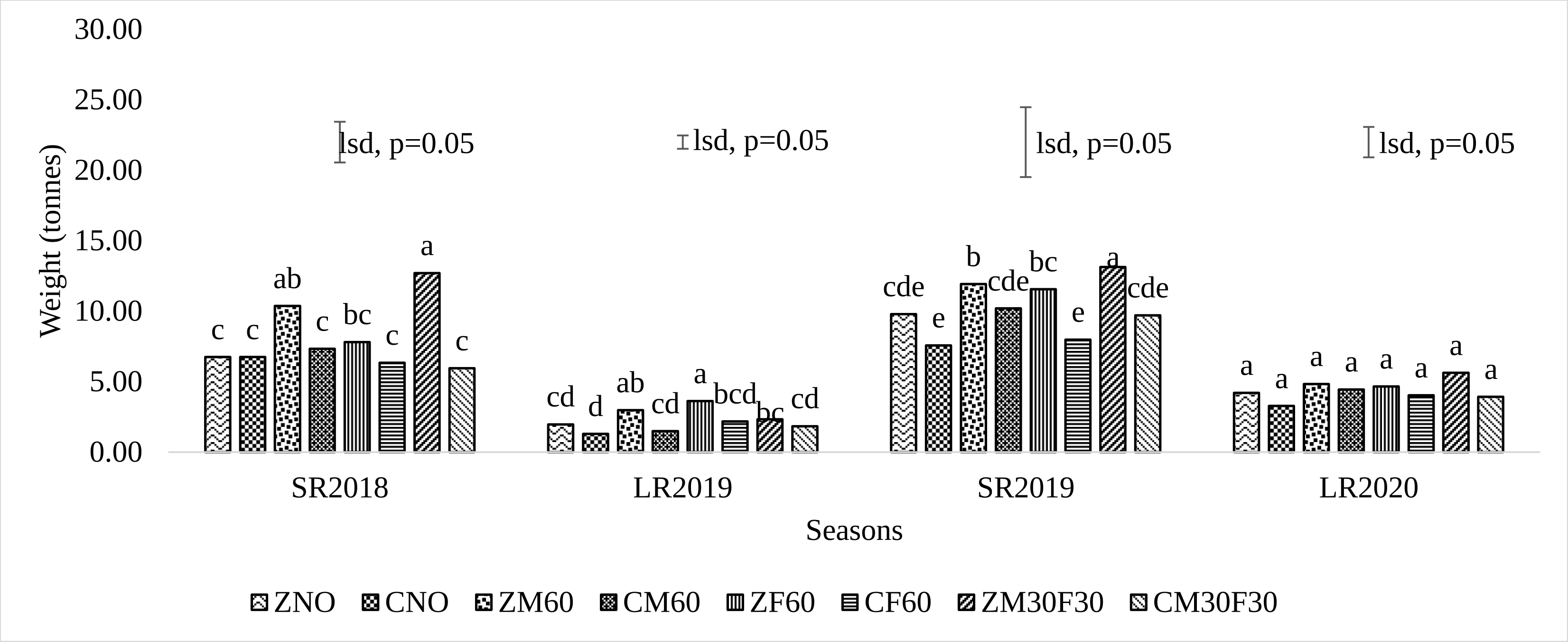
Means with same superscript letters in the same column denote no significant difference between treatments at $p \leq 0.05$ *(*=significant at* $p \leq 0.05$ *between SR2018 and LR2020 seasons, LSD= Least significant differences between* means, *ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+ 60* $kgNha^{-1}$*, CF60=Conventional+ 60* $kgNha^{-1}$*, ZM30F30=Zai+ Cattle manure+ 30* $kgNha^{-1}$*, CM30F30=Conventional + Cattle Manure + 30* $kgNha^{-1}$*).*

Appendix 7: Sorghum grain yields (t ha^{-1}) during the 2018 short rains, 2019 long rains, 2019 short rains and 2020 long rains seasons at Kabati (Figure 4.2)



*(SR18= short rains 2018, LR19= long rains 2019, SR19= short rains 2019, LR20= long rains 2020, ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+60kgNha^{-1}, CF60=Conventional+ 60kgNha^{-1}, ZM30F30=Zai+ Cattle manure+ 30kgNha^{-1}, CM30F30=Conventional + Cattle Manure + 30kgNha^{-1}). The Error bar denote the least significant difference (lsd) per season at $p \leq 0.05$. Different letters denote significant difference between treatments at $p \leq 0.05$)*Appendix 8: Sorghum stover yields (t ha^{-1}) during the 2018 short rains, 2019 long rains, 2019 short rains and 2020 long rains seasons at Kabati, Kitui County.

Appendix 9: Sorghum stover yields (t ha^{-1}) during the 2018 short rains, 2019 long rains, 2019 short rains and 2020 long rains seasons at Kabati, Kitui County



(SR2018= short rains 2018, LR2019= long rains 2019, SR2019= short rains 2019, LR2020= long rains 2020, ZNO=Zai with no inputs, ZM60=Zai + Manure, CM60= Conventional + Manure, CNO= Conventional with no inputs, ZF60=Zai+ 60 kgNha^{-1}, CF60=Conventional+ 60 kgNha^{-1}, ZM30F30=Zai+ Cattle manure+ 30 kgNha^{-1}, CM30F30=Conventional + Cattle Manure + 30 kgNha^{-1}.). The Error bar denote the least significant difference (lsd) per season at $p \leq 0.05$. Different letters denote significant difference between treatments at $p \leq 0.05$)